DECISION-SUPPORT SYSTEMS FOR ESTABLISHING RADIATA PINE PLANTATIONS IN THE CENTRAL NORTH ISLAND OF NEW ZEALAND

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SYMBOLS

Symbol		Units
AF	Rated importance of antigerminant action	Integer
AG	Weighted expression of herbicidal antigerminant action	Real number
B	Block effect in analysis of variance	
CF	Rated importance of chemical cost	Integer
cm	Centimetres	
CST	Chemical cost	New Zealand dollars
d	Differential	
D	Number of trees destructively sampled	Integer
DAP	Diammonium phosphate	
dbhob	Diameter at breast height outside bark	Centimetres
e	2.71828182846	
E	Effectiveness of a weed control treatment	Real number
exp	e to the power of the expression which follows in parentheses	
G	Basal area	Square metres per hectare
h	Height	Metres
ha	Hectare	
I.D.	Identifier	
k	Allometric capacity of stand to grow when G=0	Square meters per hectare
KF	Rated importance of weed kill	Integer
LAI	Leaf area index	Ratio
log	Natural logarithm of the expression which follows in parentheses	
m	Meters	
M	Mortality	Percentage
N	Number of stems	Integer/hectare
RCD	Root collar diameter	Centimetres
RGM	Relative growth modifier	
S	Survival	Percentage
T	Time	Years
V	Independent variable	
WK	Weighted sum of kill achieved with herbicide	Real number
f	Function of	
α	Parameter	Real number
β	Parameter	Real number
δ	Parameter	Real number
ε	Residual in analysis of variance	
μ	Mean in analysis of variance	
∞	Infinity	
%	Percentage	

ABSTRACT

A framework for decision-making relating to establishment of radiata pine plantations was defined, with provision for both numerical models and non-numerical representations of knowledge.

Data from Nelder-design experiments were used to investigate the amount of between-tree competition occurring in young radiata pine plantations. Dbhob was found to be unrelated to initial stocking prior to year five. Modelling of basal area/ha growth and yield in a Nelder-design experiment showed that functions used in traditional basal area models under-estimated basal area growth during the two years following the time when mean height was 1.40 m. An adjustment was made to these functions, allowing for allometric assumptions on which growth models are based, which improved model estimates of early basal area/ha growth.

Models of young radiata pine survival and size class distribution models were built for crops aged 0 to 5 years in the Central North island region of New Zealand. Data came from site preparation experiments, and the models are sensitive to variations in altitude and site preparation practices. Of site preparation practices studied, weed control was found to have the largest effect on both initial survival and growth. Mounding improved growth to a lesser extent, and cultivation improved survival of young trees. Fertilisation with nitrogen and phosphorous was found to have a negligible effect on growth and no effect on tree survival. The basal area/ha function incorporated the allometric adjustment developed during the

analysis of Nelder-design experiments in a way which resulted in compatible mean height and basal area/ha models.

As an illustration of the potential for non-numerical decision-support tools, a knowledge-based computer program was developed to assist forest managers in selecting herbicidal treatments prior to, or during the years following plantation establishment. The system was built using techniques developed for artificial intelligence applications, in a form which allows updating of knowledge relating to weeds, herbicides, surfactants, application methods and treatments, by experts unfamiliar with computer programming.

Opportunities for incorporation of these tools into a comprehensive decision-making and control system are discussed.

CHAPTER I

INTRODUCTION

Forest plantation establishment is a time of opportunity for forest managers, provided that they have access to the right information. Studies described here are aimed at developing appropriate structures for the information required, so ensuring that decisions are made efficiently and effectively.

The annual cost of site preparation and planting in New Zealand's plantations was estimated to be NZ$19.5 million in 1987, based on returns from a nationwide questionnaire. It was expected that 33 000 hectares of plantation would be either replanted or newly planted (Trewin & Mason 1991), representing a cost of NZ$590/ha, an amount which reflects the widely held perception that establishment treatments strongly influence crop profitability. Quantitative and qualitative representations of the establishment system would help managers make decisions about how best to establish stands in certain circumstances.

Managers have a range of alternative actions which can be incorporated into a plantation establishment strategy. Two factors are crucial for good establishment:

(i) the state of the seedling immediately after planting;

(ii) the state of the site in which the seedling grows.

Seedling state can be modified by genotypic selection (Shelbourne 1986), nursery practice (Menzies 1986, 1988), handling practice during transplanting (Trewin & Cullen 1985, Trewin & Hunter 1986), and planting (Mason 1985).

The state of a site can be improved by land clearing (Mason & Cullen 1986b), cultivation (Mason & Cullen 1986b), fertilisation (Hunter & Skinner 1986), and weed control (Preest 1985) operations. The quality of a site can be inadvertently worsened by land clearing (Ballard 1978a) and by harvesting operations (Murphy 1983).

In experiments testing alternative establishment strategies, variables can be measured during the first five years which directly affect plantation profitability. Reductions in mortality after seedling transplanting, reductions in stem defect and increases in crop uniformity all contribute to a reduction in the numbers of seedlings required per unit area to achieve a desired crop quality. More rapid initial height growth means that trees spend less time with their crowns close to the ground, where temperature extremes and weed competition pose risks.

Long-term benefits from gains generated during establishment include reduced stem defect and more rapid growth. The value of long-term benefits has been estimated in only a few cases (eg: Balneaves & McCord 1990, Wilhite & Jones 1981). The most cost-effective establishment strategy needs consideration of both short- and long-term effects, and is likely to vary from site to site. Managers need access to the best possible information before deciding on how to establish crops so that all potentially worthwhile benefits can accrue. An establishment decision-support system to assist forest managers in this regard should comprise both mathematical models and knowledge-based representations so that all relevant factors are considered in an integrated fashion.

Early growth of tree crops up to age 3 years has not been modelled quantitatively in New Zealand. Growth and yield modelling techniques will need modification in order to accommodate factors relevant to plantation establishment. Current growth and yield models are sensitive to changes in stand density such as pruning and thinning, but rarely allow for changes in site quality other than site index, nor do they allow for alterations in seedling quality, site preparation, and weed competition.

Precise models which describe the effects that differences in the condition of seedlings and/or artificial changes in site have on crop performance are likely to result from careful, process-oriented research. Much of this research remains incomplete.

There exists, however, a large database of field trials testing the effects of alternative site preparation strategies on the survival, growth, and in some cases stem form, of radiata pine (*Pinus radiata* D. Don) in New Zealand (Mason 1991a). A summary of this information in the form of models of initial radiata pine survival and growth, with inferences about the likelihood and magnitude of site preparation effects for particular sites, would be a valuable decision tool for managers to utilise.

Knowledge-based programming techniques could be used to represent non-numeric information concerned with designing establishment strategies (Mason 1991b). Ultimately, when models and knowledge-based systems are further refined, they can be combined to form a comprehensive decision-support and management information system (Mason & Whyte 1992).

1.1 STUDY OBJECTIVES

Three objectives have been set for the work reported here, with the aim of defining a framework for a decision-support and management control system for plantation establishment.

1) <u>To assemble as many existing data relating to radiata pine crop establishment in New Zealand as possible in a form suitable for later analysis.</u>

There exist at least 130 experiments relating to site manipulation before or immediately after establishment (Mason 1991a). One objective, therefore, was to assemble information relating to these data, and summarise a subset relating to the Central North Island region in a consistent format on computer.

2) <u>To develop models of radiata pine initial survival and growth which reflect a wide range of site qualities and treatments in the Central North Island region.</u>

Using the existing database of site preparation experiments and early growth plots, the objective was to develop models of the likelihood of radiata pine mortality during the first five years of a rotation.

Using the same data set, it was also proposed to develop a size class distribution model for radiata pine applicable to the first five years of a rotation. An important component of modelling was to determine the extent of between-tree competition during the first five years, and this was to be achieved by analysing data from Nelder design spacing trials.

Attempts were to be made to include in the models independent variables such as age, initial (unmodified) site description variables (altitude, rainfall, temperature, distance from the sea), and site modification treatments (cultivation, weed control, and fertilisation).

There was also a need to evaluate the factors within experiments which affected the frequency of toppling (see glossary), as this is an important cause of stem defect (Mason 1985). Few experiments were available where toppling incidence was recorded, and it was anticipated that the analysis would include data from experiments established in several regions in New Zealand.

Development of a model for the Central North Island region necessitated the development of a modelling framework for very young stands which could eventually be used to represent initial stand development in other regions, preferably through the addition of additional independent variables rather than as regional versions of the model. These extensions will be the subjects of future research, but the aim of the studies described here was to develop an appropriate framework.

3) <u>To build a knowledge-based system which assists managers with herbicide selection during the design of vegetation management regimes.</u>

Vegetation management was known as "weed control" until recently when it was recognised that the optimum strategy for dealing with weeds often lay with retaining certain species of easily controlled weeds in order to prevent the establishment of those which were difficult to control. Much of the information used to design vegetation management strategies is of a factual or heuristic nature, and it was anticipated that artificial intelligence, specifically "knowledge-based programming" techniques, might be an effective way of representing and evaluating this information.

A decision-support system of this kind was expected to provide a means of learning and evaluating computer programming techniques which may eventually be used to develop a complete decision-support and management information system for plantation establishment. The development of a complete commercially useable system was considered to be beyond the scope of the studies described here, but prototype versions have been produced that are already being implemented by at least one major company.

To provide better understanding of the nature of the problems being tackled here, a review of literature pertaining to plantation establishment, knowledge-based programming, and growth and yield modelling has been conducted and is reported in the next chapter.

CHAPTER II

REVIEW OF PERTINENT LITERATURE

A decision framework for forest plantation establishment should recognise at least three components: plantation establishment operations; growth modelling; and knowledge-based computer programming. Aspects of these three components will be examined here, and literature pertinent to them reviewed.

II.1. PLANTATION ESTABLISHMENT SYSTEMS

A conceptual model of plantation establishment is shown in Figure II.1. The state of a stand prior to first thinning (which, for radiata pine in New Zealand, is often at age 5), is a function of the condition of seedlings immediately after planting and of the prevailing micro-environments between the time of planting and that of thinning the crop. The micro-environments can be altered through field management practices, and the seedlings' condition can be altered both by field management and nursery management practices. Costs are a function of the management practices employed and site characteristics. Initial stocking may be selected on the basis of the desired number of crop stems, if survival and stem form can be predicted.

This concept can be expanded to include components of field management, nursery

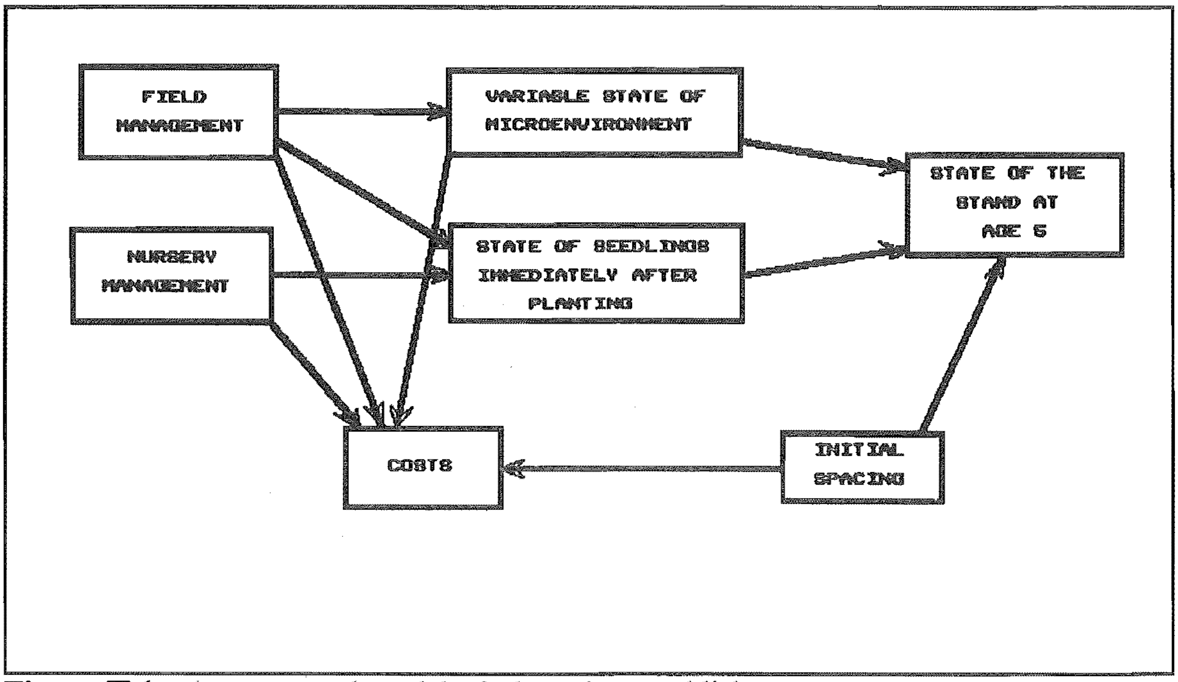

Figure II.1 - A conceptual model of plantation establishment

management, site characteristics, and seedling condition. Discussion of establishment systems will be made with reference to Figure II.2, an extended version of Figure II.1.

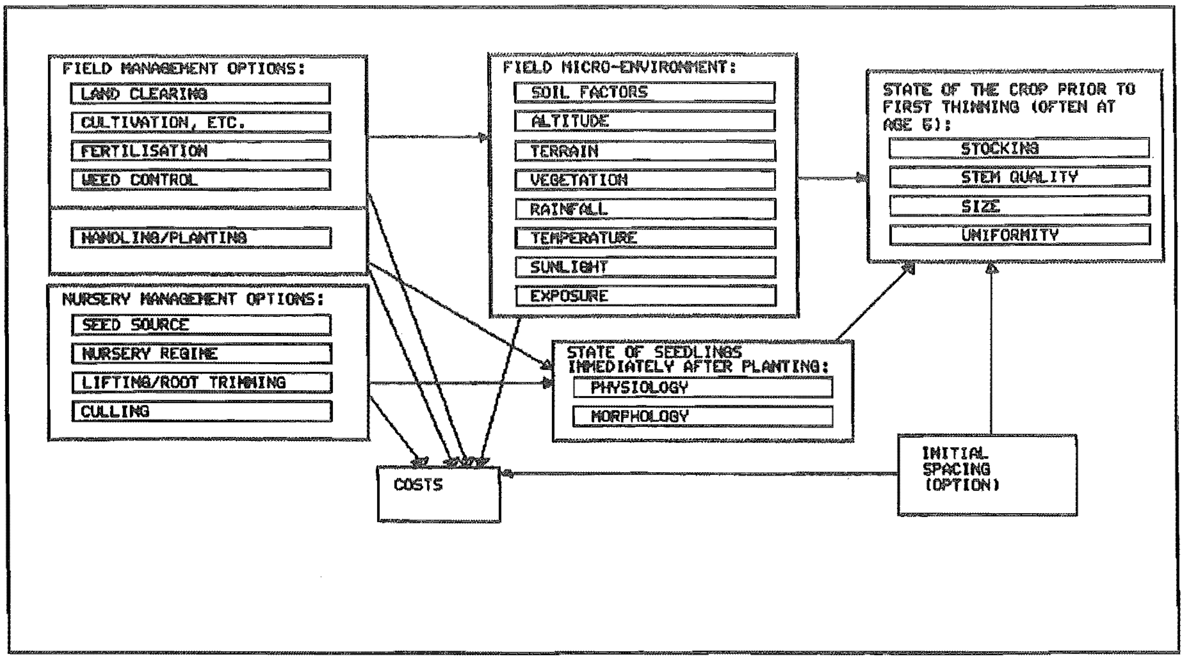

Figure II.2 - An extended conceptual model of establishment

1) Objectives of establishment

Establishment of *Pinus radiata* has been viewed as a cost to be incurred before the real decision-making could begin. This is perhaps best illustrated by the fact that the Silvicultural Stand Model (Silmod) developed by the New Zealand Forest Research Institute contained no models of juvenile stand development (program EARLY began at age 4), and allowed for no estimation of the benefits of establishment decisions; only an establishment cost was used in the analysis (West *et al.* 1982, Whiteside & Sutton 1983). In fact, the emphasis within program EARLY was on modelling the effects of management practices which altered tree crowns, and estimating the effects of site quality was left up to users.

Traditionally, the most emphasised measures of juvenile crop performance have been survival and initial height growth (eg: Chavasse 1977, Chavasse 1981, Menzies and Chavasse 1982). High survival was needed to ensure adequate crop spacing, and rapid initial height growth was desired to minimise the trees' susceptibilities to frost, weeds, or other damaging agents in the micro-environment near ground level (Chavasse pers. comm.).

More recently, researchers have begun to explore how establishment practices affect other variables in the short term, such as crop uniformity (West 1984, Mason & Cullen 1986), stem form (Shelbourne 1986), and juvenile tree stability (Mason 1985, Mason & Cullen 1986, Mason *et al.* 1989).

On any particular site, strategies for plantation establishment could be designed to achieve a specific number of stems per hectare suitable for selection as crop trees, rapid initial growth, and uniformity of crop size and spacing prior to the first thinning (Figure II.2).

a) Numbers of stems suitable for selection. Success of establishment is often expressed in terms of survival, but this measure on its own is inadequate. On some sites some surviving trees are worth little due to low vigour or stem defects. A better indicator of success would be the number of stems prior to first thinning which could qualify as potential crop trees. Common stem disorders are low vigour, ramicorns, basket-whorls, fox-tails, double leaders, pith eccentricity, sweep and speed wobble (see glossary). Some of these defects are a function of genotype (Shelbourne 1986), but low vigour and double leaders are often induced by pathogens (Alma & Nuttall 1986), while speed wobble (see glossary), pith eccentricity, and sweep are often caused by wind (Mason 1985). Any one of these defects could lower the value of the crop if defective trees have to be retained in the harvestable crop.

Managers commonly plant more trees than required for a final crop in anticipation that substantial numbers will either die or be unsuitable for selection as crop trees. The ratio of numbers of trees planted to numbers retained in the final crop is known as the "selection ratio". The relative importance of stem straightness, leader condition, and vigour for crop selection during thinning has been debated at length (eg: Sutton 1973).

Sutton (1973) provided evidence that stem condition should be regarded as the highest priority during crop tree selection. Consequently, assessment of stem quality should be undertaken in experiments designed to test alternative establishment strategies. Timber grades obtained from unpruned logs are strongly influenced by branch size and, for pruned logs, the small end diameter, size of the defect core, and conversion factor strongly influence the values of logs (Park 1980). Mill studies have indicated that percentage of conversion of round logs to sawn timber is strongly related to log size and sweep (Whiteside 1982). Mason (1985) estimated that, on the basis of these studies and measurements of individual trees, stem sinuosity caused by toppling of radiata pine in the Central North Island of New Zealand could result in losses of clear timber amounting to thousands of dollars per hectare. Sinuosity of stems also induces the production of large quantities of reaction wood, resulting in defects during curing, and in lower yields of pulp (Harris 1977). Trees with multiple stems can be included in the crop if one of the stems is severed, but growth of the largest stem would be less than that of adjacent single-stemmed trees (Mason *et al.* in prep). Sutton (1973) showed that trees sometimes recovered from leader malformation. However, managers generally assume that all defective stems are undesirable, and aim to remove them from the crop during thinning.

How much should be spent to improve the percentage of acceptable stems prior to thinning cannot be accurately calculated because existing knowledge about the effects of juvenile stem form on timber values is inadequate. There is some doubt as to the extent to which defective stems are removed in current thinning operations.

It is clear that, to be effective an establishment decision-support system should include a representation of stem defect. Few of the data available from site-preparation experiments include measures of stem defect, however. Modelling of toppling frequency went some way towards making up for this deficiency, and a model of initial tree survival was built from the available data.

b) Growth rate. During the establishment phase, tree dimensions are usually represented as diameter at the root collar (RCD) and/or height of the stem. RCD tends to be more variable than diameter at breast height outside bark (dbhob), so researchers often begin measuring dbhob as soon as all but the runt trees are tall enough. Managers are generally interested in dbhob rather than RCD, because models of growth after the establishment phase incorporate basal area/ha as a state variable (Garcia 1988). The data from site preparation experiments often included root collar diameter (RCD) instead of dbhob, which limited the sensitivity of the initial basal area models that were constructed.

Mean top height (MTH), the average height of the 100 largest diameter trees per hectare, is considered more useful than the arithmetic mean height after trees begin to compete, because it is not much affected by stocking (Beekhuis 1966). In a closed stand, mean height can be affected by stocking, with more runt trees at higher stockings. MTH is much less useful during the establishment phase, because, in the absence of between-tree competition, MTH can be expected to be related to stocking. In the study described here, models up to age 5 were built of arithmetic mean height and height distribution, both of which variables were more likely to be independent of stocking; MTH could then be derived from the distribution model once stocking was known.

c) Uniformity of tree size & spacing. Traditionally, for comparisons of establishment strategies, emphasis has been placed on survival and rate of growth in either mean height or mean diameter. Crop uniformity is also important, however, and should be represented in a decision-support system for establishment. Initial stocking at time of establishment could be close to the desired final crop stocking in uniform crops, since each tree would fit the size criterion for crop trees. Uneven crops, on the other hand, are more expensive to treat silviculturally, and need at the present time between 3 and 5 seedlings to be planted for every 1 to be retained in the final crop, depending on the quality of seedlings and the growing conditions prevailing. Crop tree selection is more difficult, the greater the lack of uniformity. Each tree, moreover, may have to be pruned to a different height (Knowles 1986). However, values of improvements in juvenile crop uniformity are hard to estimate without more analysis of pruning and thinning operations in stands of varying uniformity, and more studies of the development of crown dominance in stands. Chavasse (1981) reported verbal comments from W.R.J. Sutton at a symposium:

> "The more uniform the crop, and the more uniformly large the crop, the better."

It was clear from the ensuing discussion that no-one could actually specify the worth of juvenile crop uniformity in dollar terms, however.

Crop uniformity has been expressed as a coefficient of variation in height and/or diameter (Mason & Cullen 1986). Whilst this is a useful statistic, modelling diameter and possibly height distributions of trees during the establishment phase would allow an interface between models of initial growth and of diameter distributions at later ages, and would also enable managers to get a visual representation of predicted crop variation.

Uniformity of crop spacing is less important than uniformity of size. Sutton (1981), reported that there was no evidence of differences between rectangular spacing and square spacing in terms of effects on crop productivity or branch size. Studies of the effects of "blanking", that is replacing dead seedlings a year after the original planting, have shown that blanking in gaps up to 100 m^2 had no influence on the size of branches on crop trees, and that blanked trees were rarely selected as crop trees (Chavasse *et al.* 1981). Grace (1990) used a simulation comprising models of light interception, net photosynthesis and carbon allocation, to show that square spaced, 10-year-old radiata pine trees were more productive than equivalently shaped, rectangularly spaced trees. If the spacing had been set at time of planting, it is possible that the trees at different arrangements would not have been equivalently shaped, but the question of regularity of spacing should perhaps be re-examined in the light of Grace's finding.

d) Correlations between measures. Measures of initial crop performance described above are often correlated, both within experiments on the same site, and, to a lesser extent, between sites. Rapid initial height growth is usually accompanied by rapid diameter growth, and also often associated with crop uniformity and low mortality. More rapid initial height growth means that trees spend less time with their crowns close to the ground, where temperature extremes and weed competition pose risks. Treatments designed to reduce these risks need to last for shorter periods if growth is rapid, and may therefore be cheaper. Defect frequency is less well correlated with the other measures, hcwever.

Growth rate and crop uniformity are not always well correlated. For example, slower growth due to increasing altitude might not result in as variable a stand as growth that was equivalently slowed by weed competition.

e) Use of measures of crop quality at age 5. Some of the effects of establishment practices can be directly translated into cost savings. Higher survival, for instance, if accurately predicted, may allow managers to reduce initial stocking, resulting in lower costs of seedlings, site preparation, planting, and thinning.

Long term benefits from gains generated during establishment result from improved stem form, and more rapid growth. The impact of the latter has been tested over the length of an entire rotation in only a few cases (Wilhite and Jones 1981), and most analyses of long term gains from early improvements in growth depend on certain assumptions which are discussed more fully in Chapter III.

There is a need for further research into site preparation on yield over the lengths of entire crop rotations. Managers need accurate predictions of the effects of different regeneration strategies on a range of sites. These models should provide more information than simply stand estimates of height, basal area, and stocking. They should also allow managers to estimate variations in crop uniformity and stem form resulting from alternative strategies, as outlined by Whyte (1973, 1989).

2) Seedling state after planting

"Seedling quality" is an imprecisely defined factor which can have an enormous impact on the early growth, survival, and stem form of radiata pine (Chavasse 1980). In Figure II.1 it is called more precisely: "the state of the seedlings immediately after planting". This includes both physiological factors such as water potential and nutrient reserves, and morphological factors such as height:diameter ratio and root distortion.

During the course of an experiment comparing cultivation techniques in the Central North Island of New Zealand (Mason & Cullen 1986), differences were noted between the performance of trees adjacent to the experimental block, and those within the block subject to identical environmental conditions. The two lots of seedlings came from different nurseries, while those within the experiment, moreover, were lifted, transported, and planted carefully. Planting of the experimental block and the surrounding area occurred within a period of a few days of each other. The differences between the two blocks by age five are shown graphically in Figure II.3, and were almost certainly due to differences in seedling quality immediately after planting.

The effect of seedling state after planting on crop performance has also been described by Trewin and Cullen (1985). Seedlings of high quality displayed higher survival and more rapid growth than adjacent trees of low quality.

Assessment of seedling quality is difficult. Traditionally, morphological characteristics such as sturdiness (the ratio of height to diameter at the root collar), or root/shoot balance, have been used (Chavasse 1980, Menzies 1986). However, physiological characteristics like root growth potential, water potential and nutrient reserves are also related to survival and growth (Menzies 1988). To measure root growth potential, 28 days of growth under "ideal" conditions are required, yet transport from the field site to a glasshouse may markedly affect test results. Plant water potential can readily be measured in the field with a pressure bomb, and nutrient reserves can be assessed through foliage sampling.

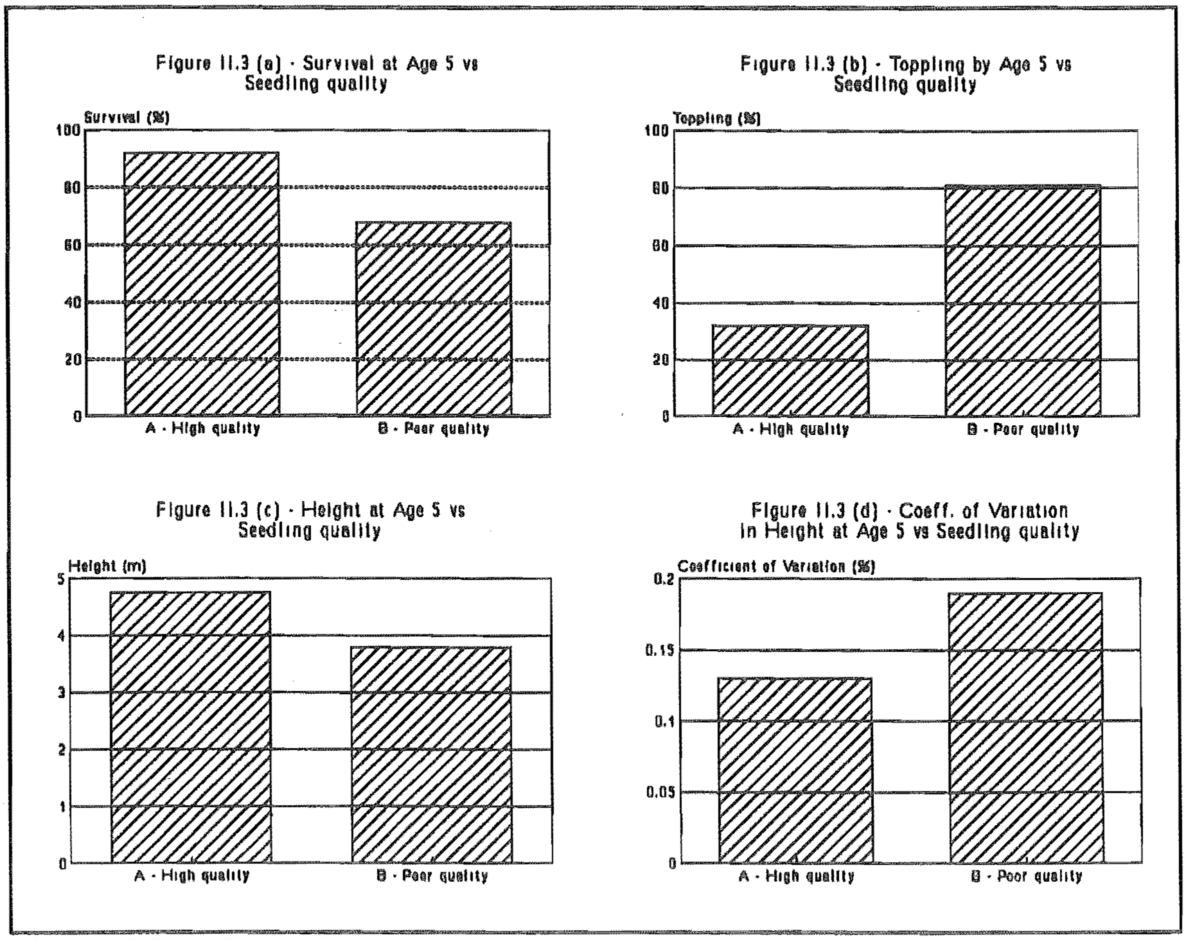

Figure II.3 - Comparison of high quality seedlings with poor quality seedlings, compartment 558, Kaingaroa Forest

Planting quality is routinely assessed by many forest growing enterprises as a check on the performance of contractors. Root placement can markedly influence juvenile tree stability (Mason 1985).

The importance of seedling quality may vary from site to site, although an experiment designed to test this hypothesis found no interactions between seedling quality and site modification with fertiliser (Trewin & Hunter 1986).

Genotypic, morphological and physiological quality, and planting practice all affect the state of seedlings immediately after planting (Chavasse 1980). Not only can these factors be difficult to measure, but they may interact.

a) Genetic improvement. Genetic improvement of radiata pine seed used in New Zealand has been an on-going process since the 1950's, when collections were obtained from "plus" trees in Rotoehu Forest. Seed quality can markedly influence initial growth and tree form, and should therefore be included in a complete establishment decision-support system. Several general categories of seed quality are recognised (Vincent & Dunstan 1989):

(i) "Bulk" seed (see glossary) was collected with little reference to parent tree quality.

(ii) "Felling select" seed was collected from trees felled just prior to commercial logging in old-growth stands. Consequently, cones sometimes originated from adjacent trees rather than the tree selected.

(iii) "Climbing select" seed was collected from "plus" trees of around 20 years of age, when superior trees were easier to identify, and the origin of cones was more accurately determined.

(iv) "Open-pollinated orchard seed" is obtained from superior clones established in seed orchards.

(v) "Controlled-pollinated orchard seed" is of the highest quality, with the characteristics of both parents carefully controlled.

Early growth gains of more than 30% have been reported for controlled-pollinated seed, with an almost two-fold increase in numbers of stems acceptable as crop trees prior to thinning (Genetics and Tree Improvement Research Field, 1987).

Differences in genetic quality are classified by three acronyms: DR (Dothistroma resistant); LI (long internode); and GF (growth and form). The latter category is generally associated with a number which roughly reflects the improvement managers should expect in growth rate and consistency of acceptable stem form. The highest GF ratings are currently obtained from control-pollinated orchard seed, at approximately GF25.

In the absence of specific information about genotypes employed in each site preparation experiment, it was expected that variation in genotype would add to the residual mean squares of models built during the studies described here.

Seed of high genetic quality is in short supply, and is more expensive than lower quality seed. This has resulted in several alternative strategies to produce many plantlets from each seed. Losses in New Zealand nurseries during traditional bare-root seedling production have been recently estimated at 50% (A.R.D. Trewin pers. comm.). It is therefore important to ensure that seed is undamaged during extraction from cones, and that as high a proportion of seed as possible produces useable plants. Seed treatment is the first step in this process.

b) Seed treatment. Seed treatments include collection, extraction, drying, stratification, and storage of seeds, and coating their surfaces with fungicides, repellents or poisons (Hedderwick 1981b). These can markedly influence the proportion of collected seeds which produce seedlings of good quality.

Seed extraction from green cones involves heating, tumbling, de-winging, and drying. Rots, desiccation, and mechanical damage caused by rough handling can result in reduced numbers of viable seed per kg.

Grading of seeds by size classes has traditionally been carried out to ensure that, within any nursery bed, germination is as good and even as possible, because differently sized seeds have to be sown at different depths (Menzies 1986).

Seed are stratified just prior to sowing by soaking them for several hours. This raises the proportion of seed which germinates, and ensures that seeds all germinate within as small a time frame as possible. Seed coatings are applied to reduce seed losses due to fungi, birds and/or rodents (Hedderwick 1981a).

Seed treatments influence seedling costs more than seedling quality, and it was considered unlikely that seed treatments would have a large impact on the modelling studies reported here, although they would have an influence on decision-making once costs were included in the represented system.

c) Bare-root nursery systems (see glossary). Several traditional regeneration strategies have been tried for radiata pine in New Zealand, and almost all practitioners have now opted to employ a bare-root seedling system. Natural regeneration from cones left after harvesting was tried for several years in Kaingaroa Forest, but regeneration was very uneven, required thinning and supplementary planting, and sites could not be established with trees of superior genotype. Container systems have generally proved more costly than bare-root systems, and rapid growth of young radiata pine seedlings can result in severe root distortion within containers (Faulds 1981). Radiata pine seedlings are generally grown in nurseries for one year prior to planting, and are not transplanted within nurseries ("1/0" stock).

Selection of nursery sites and maintenance of soil fertility have been very well summarised by Knight (1981). Well drained, deep loamy sands or sandy loams are most favoured, as they have desirable workability, are not easily damaged by compaction due to machines, and are easily penetrable. These soils generally require maintenance in the form of chemical fertilisers, cultivation, and crop rotation between seedling crops and ryegrass plus clover.

Seed is sown between September and November in prepared beds, at depths which vary with seed size (Menzies 1986). Seed spacing influences field performance of planted seedlings (Bowles 1981, Balneaves 1983), and most nurseries now employ precision seed sowers (Hiscock *et al.* 1981). It is also important to minimise competition from weeds, and nursery beds are generally kept entirely weed-free.

Seed predation by birds, rodents and fungi is a serious problem in New Zealand's forest nurseries (Hedderwick 1981a). The exact extent of the problem is unknown, although it is said to account for a high proportion of the roughly 50% loss between sowing and seedling delivery. Until a comprehensive survey is undertaken of reasons for losses in different locations and at different times, solutions are unlikely to be found.

While in nurseries, young trees receive several treatments collectively known as conditioning (Rook 1971, Van Dorsser 1981, Menzies 1986). These generally consist of an initial undercut of taproots to a depth of 5 to 8 cm, when the seedlings are 20 cm tall, with a sharp, reciprocating blade, followed by periodic wrenching (displacement of root-soil contacts by passing a blunt, reciprocating blade beneath the seedlings' root systems), several lateral root prunings with disks which pass between rows of seedlings, and a final undercut a few weeks prior to seedling lifting. In some cases, topping (severing of seedling tops at a specified height) is also included, especially on exceptionally fertile sites. The exact nature and timing of operations vary with nursery fertility. The effects of conditioning on seedlings are to increase root to shoot ratios, increase fibrous root surface area, slow top growth, increase storage of carbohydrate in the roots, reduce foliar nutrient concentrations, reduce foliar chlorophyll, and reduce apical dominance of the root system. The latter three effects are considered undesirable, but the other effects improve seedling performance after transplanting. Higher root:shoot ratios reduce initial water demand of planted seedlings while increased fibrous rooting and carbohydrate storage provide a higher likelihood of root regeneration which will allow seedlings to meet their water and nutrient demands. Regulating plant size also minimises seedling transport costs.

Multi-leadered or small seedlings have been shown to perform poorly after planting, and these are generally removed from nursery beds when the seedlings are 10-20 cm tall, during an operation known as culling (Menzies 1986). Prior to 1980, culling was usually carried out after lifting, in sorting sheds, but this extra handling resulted in inferior growth and survival of seedlings in the field (Trewin & Cullen 1985).

Nursery practice clearly has a major influence on tree performance after planting, and it was expected that variation in practices applied to trees in different site preparation experiments would add to the residual mean squares of predictive models. However, during the establishment of experiments used in this study, every effort was made to ensure the highest possible standards of nursery practice, and the resulting models should apply to tree crops established by managers who have made similar efforts.

While bare-root seedling production has proven very cost-effective for lower genetic quality seedlots, the scarcity and high cost of seed of improved genotypes has led to the development of several tree propagation techniques which would be prohibitively expensive for normal seed, but which may allow several trees to be grown from each seed. These include cuttings, tissue culture, embryogenesis followed by artificial seeds, and other biotechnological techniques.

d) <u>Cuttings</u>. Cuttings can be collected from existing trees, clonal hedges (Faulds 1981a), seedlings which have been topped, or seedlings which have been pulled into a horizontal position (Faulds & Dibley 1989). Cuttings are placed directly into prepared nursery beds, and can then be conditioned and transplanted in a similar manner to normal bare-root seedlings. Juvenile cuttings are currently considered best, owing to reductions in growth rate of older cuttings attributed to physiological age (Menzies *et al.* 1991).

Arnold (1991) reported replication rates from four to 50 fold, two years after seed sowing for cuttings systems. He argues that multiplication of seed through cuttings would only be worthwhile where seed costs exceed $1800/kg or where seed is particularly scarce.

Data available for the studies described here were obtained from cuttings in only a few instances, and the final analyses were restricted to data obtained from stands established with bare-root seedlings.

e) Tissue culture. Propagation from embryonic tissue allows higher seed multiplication rates than that from cuttings, but is currently more expensive per plant. The process involves the sterile culture of cotyledons from partially germinated seed; hormonal treatment to induce root formation; propagation of roots on the shoots under controlled conditions; hardening off (see glossary) of plants so they can withstand ambient conditions; and lining out in either a nursery bed (where they are subsequently treated in a similar fashion to bare-root seedlings) or into containers (Smith & Aitken 1981).

Opportunities may exist for extensive use of tissue culture to multiply the usage of high quality seed, but effective mechanisation of the process would be required for it to be cost-competitive with other techniques.

f) Artificial seeds (see glossary). An alternative strategy for seed multiplication which is under development is to place individual tree embryo cells into a bioreactor where they duplicate themselves. They are then stimulated to produce new embryos by hormones absorbed from an agar preparation, and then placed within artificial seeds which can be used to produce bare-root seedlings using standard nursery systems. Multiplication rates of tens of thousands for individual seeds are theoretically possible through such a process, and work is continuing in an effort to improve the rate of embryo formation from replicated cells, and to ensure artificial seeds are adequately protected by a non-living seed coating.

g) Seedling handling. Seedlings of the highest quality genotype propagated by the most successful technique can be ruined during transport from nursery to the field planting site unless adequate care is taken (Trewin & Cullen 1985, Trewin & Van Dorsser 1985, Balneaves 1987). Emphasis is placed on an integrated approach, culling defect seedlings from nursery beds, lifting and packing well-formed seedlings horizontally into cardboard cartons, which are then stacked into crates for transport to planting sites. The crates serve as temporary stores in the field for seedlings. Seedlings are only handled at lifting and during planting, and an attempt is made to minimise the elapsed time between the two events. The system was designed to minimise mechanical damage to seedlings, and to facilitate scheduling and control of transplanting operations.

When there is a delay between lifting and planting of seedlings, cool storage is necessary. Prolonged storage of radiata pine seedlings results in diminished crop performance (McCracken 1979).

Recent work has demonstrated the importance of maintaining seedling water potential during transplanting by lifting during mornings or late afternoons (avoiding the period of maximum water deficit in plants' diurnal cycles) when vapour pressure deficits are low, and ensuring that roots are kept moist if any period of storage is necessary (Balneaves & Menzies

1990).

h) Planting. Planting can influence crop quality markedly. Where roots are poorly trimmed, or motivation and supervision of planters are poor, roots can be badly distorted, resulting in juvenile instability (Mason 1985) which is an important problem in New Zealand's plantations (see Chapter VI). Most planting in New Zealand's plantations is performed with spades; mattocks having been abandoned due to their tendency to encourage swept roots (Balneaves & Cullen 1981). Evaluation of planting practices has been hampered by poor definitions of terms describing planting techniques. Important elements of planting methods would appear to be:

(i) selection of planting spot;

(ii) extent of screefing and cultivation of planting spot;

(iii) depth and width of planting hole;

(iv) placement of seedling;

(v) straightness of roots - usually achieved with a 10 cm "pull up" after the soil has been replaced;

(vi) the degree of compaction of soil around the roots.

Recommendations relating to these elements have been made by Trewin & Cullen (1985). Some questions remain about the effects of various actions incorporated in planting methods on ergonomics and crop stability. These would be best investigated by means of experiments with each element as a factor, implemented over a variety of site conditions.

While variation in handling and planting quality undoubtedly added to the residual sums of squares in the analyses described here, it should be noted that great care was taken during handling and planting of trees intended for experiments.

The highest quality seedlings, handled carefully, and well planted will perform poorly if conditions of the planting site are too severe. Site factors are complementary to seedling condition in determining the state of a crop prior to first thinning, but it should not be considered independently of seedling quality.

3) Site factors

Site factors have an enormous impact on initial seedling performance, and can often be changed by appropriate management practices. Soil within plots on a site at Takou Bay in Northland New Zealand, for example, was cultivated with a ripper tine and a bedding plough prior to planting (E. G. Mason, unpublished data). Soil within adjacent plots was not cultivated. A comparison of the performance of seedlings within the cultivated and uncultivated plots is shown in Figure II.4.

a) Site variation. Forest site productivity is often expressed as site index (the mean

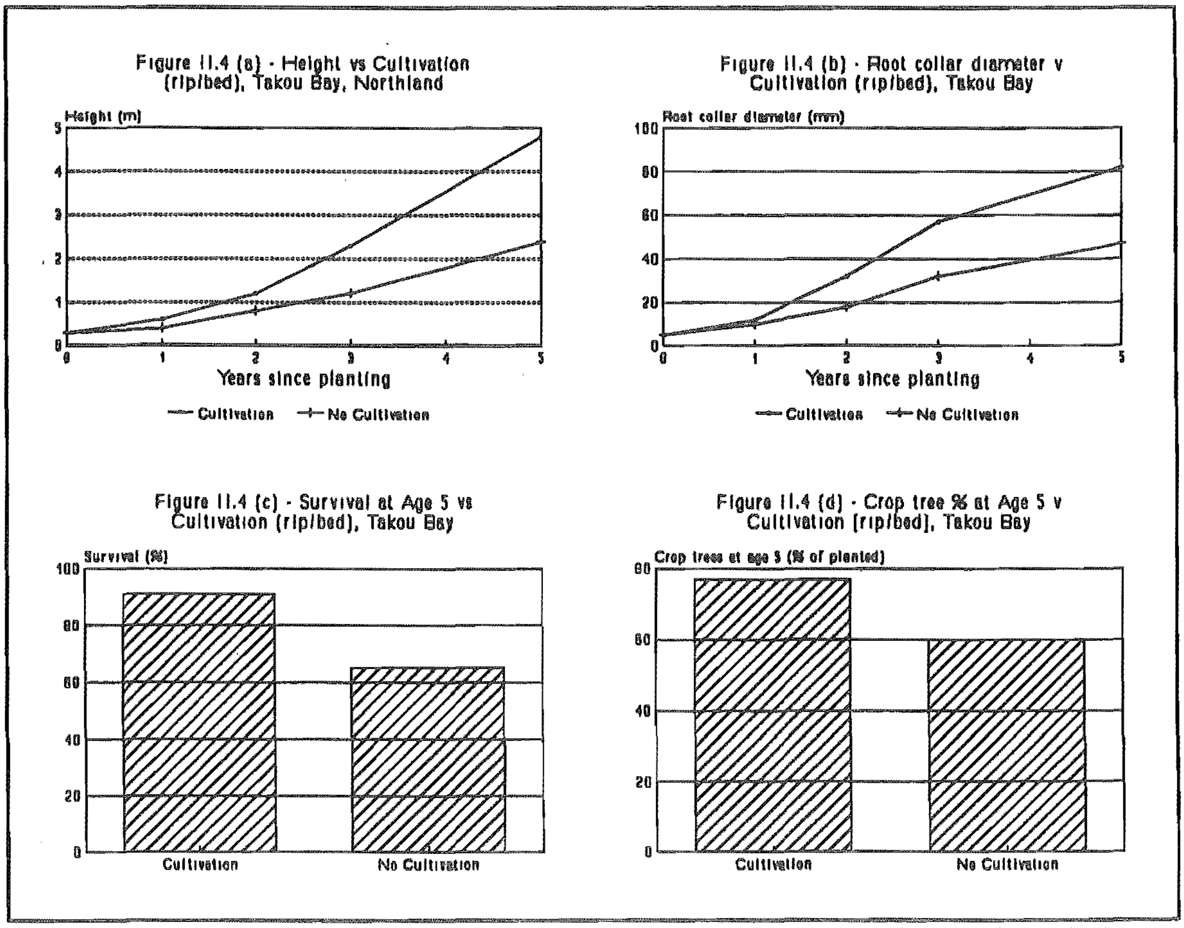

Figure II.4 - Comparison of tree performance on ripped/bedded and uncultivated plots at Takou Bay, Northland

top height of a stand at an index age), but this measure does not define factors affecting productivity which might be changed by management, and hence has very limited utility as a state descriptor during the establishment phase. The microsites in which juvenile trees grow can be radically altered by management practices, and this is the main focus of the studies described here.

Important factors affecting crop performance are likely to include measures of relative humidity, CO_2 partial pressure, insolation, wind, rainfall, slope, soil nutrient status, soil drainage, weeds, temperature, and incidence of frost. The last five of these can be affected by management practices, both adversely and favourably.

b) Effects of harvesting. Harvesting operations can damage sites by displacing topsoil from areas used for roads and landings, spreading weed species by machines, and compacting soil during skidding operations. In addition, slash and stumps left on site can increase costs of future operations, reduce initial crop performance by changing microclimates, and, in the case of slash on some sites, help to maintain site productivity.

Murphy (1983) found that survival and growth of juvenile trees on skid trails left after logging were substantially less than those of trees growing on undisturbed areas of Tairua Forest, on the Coromandel peninsula, New Zealand. Damage to the site included soil compaction and removal of topsoil.

Access to a site can be hindered by slash, and stump numbers can influence the productivity of mechanical land clearing operations (Mason & Cullen 1986).

The extent to which slash is removed from a site during harvesting or land preparation can influence initial crop performance and long-term productivity in contradictory ways. Clearing slash from a frost-prone site can increase initial tree survival and growth dramatically (Washbourne 1978). However, slash removal can result in a long term loss in productivity (Ballard 1978a). Madgwick & Webber (1987) estimated that removal of foliage during harvesting operations in northern Kaingaroa would amount to a 29% additional removal of dry matter, but additional nutrient loss of between 80% and 170% (depending on the nutrient). Often the amount of slash left on a site after logging is greater when a pulp market is not available (Hall 1991).

Apart from the effects of logging, site manipulation is usually an intentional attempt to improve future crop profitability. The decision to apply a particular treatment generally requires information from two different, but related perspectives:

(i) biological/silvicultural perspective - information about the response of the plants to the treatment;

(ii) logistical perspective - information relating to the feasibility of the proposed treatment, including costs.

These two perspectives can rarely be completely separated. The response of the plants to one treatment may affect the logistics of a subsequent treatment. For instance, a treatment which makes the crop more uniform may allow a reduction in initial stocking and lower pruning and thinning costs. Wider spacing may make mechanised operations feasible. Sometimes the effects are even more direct; cultivation on compacted sites can reduce planting costs (P. Hall pers. comm.). Knowledge-based programming offers an effective means of synthesising the two perspectives ((i) and (ii) above).

c) Land clearing. Mechanical land clearing options, their limitations and productivity have been listed by Mason & Cullen (1986b). Techniques vary according to the nature of debris on the site, soil conditions and slope. Fire has been popular as a land clearing tool on sites where slash has had time to cure and where soil nitrogen reserves have been high, but the operation has been little studied in New Zealand, despite its former widespread use.

The aims of land clearing are to facilitate site access, reduce competition from weeds and provide a microsite for young trees which encourages survival and rapid initial growth (Mason & Cullen 1986). This last aim is especially important on sites prone to autumn or spring frosts (Washbourne 1978).

Clearing sites mechanically can reduce long-term site productivity, especially where slash and litter are removed from large areas of a site (Ballard 1978a, Dyck & Beets 1987). There is an urgent need to develop and evaluate land clearing methods which meet managers' initial requirements without compromising long-term site productivity. An example of such a treatment may be windrowing with a root-rake mounted on the arm of an excavator, as demonstrated at Geraldine forest late in 1991. The machine travels only down the centre of windrow bays, and there is a minimum of skewing of the machine tracks, and minimal litter disturbance. Line blading with root rakes is another possibility, as is roller crushing of slash on sites where frost is unlikely.

In the study described here, there was too limited a range of land clearing options represented in the database for the effects to be included in models. Most experiments were on pasture sites or sites where slash had been burnt.

d) Cultivation/drainage. Mechanical techniques designed to alter soil structure and improve drainage have been described elsewhere (Cullen & Mason 1981, Mason & Cullen 1986b). They consist primarily of drainage networks dug with an excavator for very wet sites, ripping with winged tines, mounding with disks, and mounding with v-blades (which is also considered a land clearing technique).

Some general trends in cultivation experiments are evident, which may be quantifiable. The largest increases in growth due to cultivation have often occurred on excessively wet sites with heavy soils, especially in Northland, Westland and Southland (eg: see Hetherington & Balneaves 1973, Williamson 1985). These trends are consistent with those in the southern United States, where creating mounds with disks is primarily a means of draining wet sites (Derr & Mann 1970, Wilhite & Jones 1981, Haywood 1983, Outcalt 1984). Ripping has consistently increased root growth and stability of trees on compacted soils in New Zealand (Somerville 1979, Mason & Cullen 1986a, Mason *et al.* 1989).

Cultivation with disks was found advantageous on frost-prone, Central North Island pumice sites mainly because weeds were incorporated in the soil and mineral soil was exposed, raising the albedo of the ground surface (Menzies and Chavasse 1982). Where compacted soils were ripped in this region, the depth of root growth was increased, reducing instability, but above-ground growth was only marginally affected. Root growth of radiata pine was severely restricted when soil resistance to penetration exceeded 3 MPa (Mason & Cullen 1986a).

Experiments in the database used for this study often included ripping and/or ripping/mounding treatments, and these factors were included in the analyses.

e) Fertilisation. Phosphorous, nitrogen and boron are the elements most often deficient in New Zealand's plantation soils. Phosphorous is applied at establishment mainly on weathered and leached clays or podsolised sands in Northland, or on leached alluvial gravels in the Nelson region (Ballard 1978b). There is a need to develop an effective means of quantifying the response of radiata pine to phosphate fertilisation using a soil test as one of the independent variables.

At establishment, nitrogen is applied in the same localities as is phosphorous, but it is also regularly applied to landings throughout New Zealand in attempts to rejuvenate them after logging (Ballard 1978). There may be potential to use measurements of total nitrogen as a guide for nitrogen fertiliser application in forest crops. For crops beyond the establishment phase, Hunter *et al.* (1986) found that response to nitrogen fertilisation was related to soil total nitrogen, Bray P extraction, age at fertilising (younger ages produced higher responses), the proportion of clay in the soil, and different pruning and thinning histories. Nitrogen fertiliser applied to sites low in phosphorus was detrimental.

Boron deficiency is common in the Nelson region, and has been noted in Canterbury and parts of the Central North Island (Will 1985). At present there is no prospect of a soil test to predict boron deficiency (M. Skinner pers. comm.), and local knowledge is probably the best indicator of crop response to boron fertilisation.

Potassium deficiency occurs in Nelson on ultra-basic "mineral belt" soils, and in parts of Northland (Will 1985). Prediction of deficiency and effects of fertilisation might be made on the basis of region and soil type. Variations in the effects of fertilisation with potassium or boron on identifiably deficient sites are unlikely to be predictable with the existing young stand database (M. Skinner pers comm).

In New Zealand, very young stands of radiata pine do not commonly suffer from magnesium deficiency (T. Payn 1991). Magnesium fertilisation was therefore not considered to be an important factor in the studies reported here.

A soil nutritional atlas for New Zealand-grown radiata pine, identifies potential deficiencies of phosphorus, nitrogen, potassium, magnesium and boron by location. It was developed from a cross-referencing of foliage nutrient analyses and soil types (Hunter *et al.* 1991).

Experiments represented in the database included many where phosphate and nitrogen fertilisation treatments had been tested. It was considered that an analysis of these treatments would be feasible, but effects of other nutrients could not be evaluated because too few treatments involving them were included.

f) Weed control. Weed control commonly promotes juvenile radiata pine survival and growth in New Zealand (eg: see Richardson 1991, Glass 1985, West 1984, Balneaves 1982). This is especially so on frost-prone sites, where removal of ground cover is one of the most essential components of an establishment regime (Washbourne 1978, Menzies & Chavasse 1982).

Adequate research has been conducted into means of controlling different weed species, and while these have been effectively reported in the literature (Preest 1985, Preest & Davenhill 1986, Davenhill 1985), managers need a summary of measures appropriate to any particular weed combination, that can be easily updated, in order to design cost-effective control regimes.

Detailed studies of the effects of weeds on young radiata pine growth are needed before precise models of tree growth response to weed competition can be constructed. Radosevich (pers. comm.) has demonstrated that weed species differ in their abilities to compete with Douglas fir in Oregon, and that visual assessments of the extent of weed infestation can be related to tree growth and development.

Several of the experiments used for the studies reported here included treatments with and without weed control. The exact species and density of weeds were usually not detailed, however, a deficiency which limited the extent of analysis of weed competition effects.

g) Interactions between treatments. Identification of independent variables in an initial growth model in terms of operations applied to sites may result in significant interactions. In part this is because different treatments have similar effects on factors which affect growth, for instance, cultivation may provide some weed control and land clearing can result in surface cultivation. It is also because some treatments may be ineffective under certain conditions, notably fertilisation if weeds are uncontrolled. Interactions between fertilisation and cultivation are likely in Northland (Hunter & Skinner 1986).

Interactions between treatments were tested where possible in the studies reported here.

4) Initial stocking.

The initial stocking selected for any site is a function of:

(i) expected mortality;

(ii) expected defect;

(iii) branch size control considerations;

(iv) desired final crop stocking.

In New Zealand, selection ratios are usually between 3 and 5. On most sites, where trees are planted which have been properly conditioned, carefully handled, and well planted, and where appropriate site preparation has been used, mortality immediately after planting can be minimal. Stem defects, however, can make many trees unsuitable as crop trees. In some circumstances high initial stockings are planted in order to reduce branch diameters. Boards milled from trees with small branches are generally graded more highly than those from trees with large branches.

Data available for the studies reported here allowed an evaluation of (i) above. Too few data describing stem defect were available for an analysis of (ii). (iii) and (iv) are issues relevant to models of crops beyond the establishment phase, and the interfacing of initial growth models with models of growth and yield in older crops is discussed in II.3 and Chapter III.

This section has reviewed the information which should be represented in an establishment decision-support system. Clearly, it is a complicated system with many important components, and a complete representation would be beyond the scope of studies reported here. The aim of these studies was to define structures within which the entire system might be eventually represented, with important portions represented as examples.

The most appropriate means of representing the system is a combination of knowledge-based programming and growth modelling. Literature pertaining to these two techniques is reviewed in the next two sections of this chapter.

II.2. KNOWLEDGE-BASED PROGRAMMING

Qualitative information is often employed to make predictions about the effects of actions during plantation establishment; for example, minimising frost damage with the "frost flat" regime (Menzies & Chavasse 1982), improving the quality of tree stocks (Menzies 1988), minimising damage to tree stocks during transplanting (Trewin & Cullen 1985), and maintaining juvenile tree stability (Mason 1985). It is also used to decide how to do certain tasks. The selection of herbicides, land clearing equipment, cultivation tools, and planting techniques all involve information commonly available in the form of handbooks or manuals (Preest 1985, Davenhill 1985, Levack 1986). The problem is how to use this information profitably in routine operations.

Knowledge-based programming is a set of computer programming techniques which enable machines to represent and process qualitative, symbolic information in a logical way. They are a subset of the field of artificial intelligence. Saarenmaa (1989) comprehensively outlined these techniques within a forestry context, and Mason (1991b) summarised opportunities for them within New Zealand forestry.

Expert systems (see glossary) are a subset of knowledge-based systems which attempt to simulate on computer the decision-making activities of a human expert (Stock 1987, Saarenmaa 1989). The phrase "expert system" creates expectations of human-like computer behaviour which may be unrealistic, and excludes possibilities for knowledge-based programs which could not be attempted by less accurate and slower human brains. While it is not intended that decision-support systems should necessarily be expert systems, many of the techniques employed in expert system development are useful for knowledge-based programs generally, and they appear to have a place in solving the above-mentioned problem.

1) Development of artificial intelligence techniques

The founding fathers of modern computing were intensely interested in artificial intelligence (AI). Turing (1950), who developed the theoretical basis of programmable computing, wrote a famous treatise on artificial intelligence from a behaviourist perspective. The "Turing test" for artificial intelligence suggested that, if an interviewer could not determine whether a remotely conducted written conversation was with a machine or with a human, then the machine could be regarded as intelligent. Several philosophical objections to this definition of AI have been raised, and many of them were anticipated by Turing in his original article. It is not proposed to discuss such definitions at length here, but awareness of the flavour of the debate is helpful in utilising basic principles that underlie the problems addressed in this study.

"Artificial intelligence" is now commonly used to describe a wide range of computer applications, including machine learning, robotics, vision, natural language processing, logic, planning/scheduling, and knowledge-based systems (Saarenmaa 1989). Much of the important theoretical development of AI has been conducted by researchers who attended a meeting in Dartmouth College during the summer of 1956, their students, or their students' students (McCorduck, 1979, Stock 1987). Four stages of AI development were identified by Forsyth (1984):

(i) neural nets during the 1950's;

(ii) generalised heuristic search during the 1960's;

(iii) knowledge-representation during the 1970's;

(iv) machine learning during the 1980's.

a) Neural nets during the 1950's. Initial attempts at creating intelligent machines involved building machine or program architectures which duplicated structures found in human brains. These consisted of simulated neurons with many interconnections. At the time, success was limited with this approach, and it was later shown that existing algorithms for training the networks were extremely limited from a theoretical point of view (Minsky & Papert 1969).

b) Heuristic search. Following the limited success of early neural nets, it was proposed that intelligence might be built from object-manipulating abilities, such as pattern matching, searching, and modifying semantic structures. The "General Problem Solver"

(GPS) program was built with these capabilities, founded on a "depth-first search" approach, where a problem is successively decomposed until a point is reached where solutions can be found (Newell & Simon 1963). Its success was limited to small domains such as puzzles where rules were well defined and numbers of problem states were very limited (Forsyth 1984).

c) Knowledge representation. Expert systems, as they have been labelled in the popular literature, were founded on the idea that there was an inverse relationship between the generality (breadth of problems addressable) of an AI program and its success. It was thought that if the heuristics and relations employed by an expert in a very narrow domain could be represented in the form of a program, then a successful machine expert would result. The first such program was DENDRAL, which successfully acted as an expert in certain aspects of organic chemistry (Feigenbaum *et al.* 1971).

One of the most influential expert systems was MYCIN, developed by Shortliffe (1976) to diagnose and suggest treatments for blood diseases caused by bacteria. The system represented knowledge in the form of a large number of if/then rules, with conditions for higher level rules satisfied by lower level rules, a representation known as backward chaining. Important features of MYCIN were the inclusion of certainty factors (see glossary) to represent the probabilistic nature of inferred knowledge, the ability to explain reasoning in response to user queries, and a sophisticated, friendly user interface.

Dreyfus (1987), however, doubted the ability of rule-based expert systems to simulate the behaviour of human experts, pointing out that humans rarely used mental processes equivalent to rule-governed operations, nor did they carry out operations on determinate bits of data representing worldly facts. He identified five levels of human expertise, from novice to expert, and suggested that expert systems might be capable of only the first two (novice and experienced beginner).

Clearly, expert systems do not mimic the mental behaviour of human experts. Human experts react to patterns of experiences, and recall answers by a process known as "chunking" (Bootzin *et al.* 1986). They commonly remember about 70 000 chunks. Computer expert systems often rely more on raw computing power to examine a very large number of alternative solutions (Michie 1982).

Intelligent or not, in the 1970's computers employing knowledge-based programming were beginning to supply answers which until then had required people. MACSYMA, a symbolic mathematics program, replaced some mathematicians (Pohl 1984). MYCIN was considered very effective, and PUFF, a diagnostics program for lung diseases, had a success rate of 90% when evaluated by a panel of human experts (Stanford Computer Science Department 1980).

Well constructed expert systems have the potential to provide a permanent source of accurate, easily accessible, and reproducible advice on specific topics. The name expert system, however, tends to promise more human-like behaviour than most programs currently deliver, and can divert attention from the ways in which computer capability exceeds human mental ability. Human vision, language, and motor control functions have been estimated to involve "more power than 100 supercomputers" (Reddy 1988), and computers lack common sense. On the other hand, most humans are less adept at arithmetic than a 4 bit microprocessor, and computers are superhuman in speed, accuracy, and persistence at repetitive tasks.

"Knowledge-based programming" is a term that conveys the idea of representing and processing ideas; it neither promises too much nor restricts use of a range of programming paradigms during development to those which directly mimic human problem solving methods.

d) Machine learning. Forsyth (1984) identified machine learning as the main AI topic of the 1980's. The example he quoted was a program called EURISKO (Lenat 1982), which improved its own body of heuristic rules automatically, on the basis of experience. Automatic induction from tables is a feature of some empty expert system shells. What Forsyth could not have foreseen was the return to neural nets following a theoretical improvement in learning, known as backpropagation (Rumelhart *et al.* 1986, Caudill & Butler 1990). Although some commercial applications using neural nets have been built, their use is currently limited to problems with specific types of inputs and solutions, as discussed below.

The 1980's saw the extension of knowledge-based programming into many commercial enterprises, including forestry (Mason 1991b). Most commercial applications are based on the narrow domain, knowledge-representation approach of Feigenbaum *et al.* (1971) & Shortliffe (1976), with increasingly sophisticated mixtures of knowledge-representation techniques. Mixtures of techniques are likely to work best for the representation of knowledge relating to an establishment decision-support system.

Careful identification of the domain (problem area) in which the program will work is the first step towards a successful development.

2) Domain selection

Stock (1987) identified the following desirable characteristics of domains for knowledge-based programs.

(i) Expertise should be scarce and time consuming to learn, but the task should take only a few hours or days.

(ii) The problem domain should be narrow, but deep (highly specialised), and there should be a large number of possible solutions.

(iii) The problem solution should require heuristics (rules of thumb), ie: a set of equations could not be used to arrive at a satisfactory solution.

(iv) Competent experts must be available and willing to help with development.

(v) The problem should be financially important enough to warrant building the system.

(vi) Experts in the area should agree.

(vii) Ample data, test cases, and potential users should be available for testing the system.

An additional set of criteria, provided by Gordon *et al.* (1987), suggest that boring tasks, whether easy or hard, should be assigned to a machine, tasks which are both interesting and easy should be left to humans, while computer assistance should be provided to humans doing interesting but difficult tasks.

Given the current lack of sophisticated computer learning capabilities, knowledge acquisition from domain experts is usually the bottleneck which restricts development once a domain has been identified (Stock 1987).

3) Knowledge acquisition

The purpose of knowledge acquisition (see glossary) is to identify and organise the knowledge needed for decision-making within a chosen domain. Often, those coding knowledge into a computer are not experts in the domain, and a number of different methods have been proposed. The key tasks were summarised by Kidd (1987) as:

(i) eliciting data (usually verbally) from an expert;

(ii) interpreting these verbal data to infer the underlying knowledge and reasoning;

(iii) using the interpretation to build a model or language that describes the expert's performance.

The latter two tasks are different aspects of the same process, and often occur concurrently.

Knowledge acquisition should be completed before programming tools are selected. Poor systems would likely result from attempts to mould "reality" to fit a particular scheme for knowledge representation.

a) Knowledge elicitation. Elicitation of knowledge generally involves several different types of interaction with experts. The types chosen may vary depending on the type of knowledge being elicited.

Interviews with experts are by far the most common means of eliciting knowledge. Interviews should be conducted in a structured manner, with continuous audio taping if possible. Conversation theory can be very helpful in identifying interview strategies, and in ensuring that communication is efficient. For example, teachback interviewing, where the interviewer repeats the information back to the expert in different language has been found to improve communication (Johnson & Johnson 1987).

Transcription of interviewing sessions provides a permanent record of the process, ensures that no information is overlooked, and provides a basis for formulating questions for future interviews.

Verbal protocol is a complementary way of eliciting knowledge. An expert is asked to perform a task while providing a running commentary about the decision-making involved (Kuiper & Kassirer 1987, Fox *et al.* 1987). This eliminates the problem of inaccurate recall which can affect knowledge gained through normal interviews, but may result in only superficial compiled associations being verbalised. More formal interviews may be needed to explore why a particular decision was made or procedure adopted, and introductory sessions may be needed before the interviewer can understand what the expert is saying.

Emphasis should be placed on capturing an expert's conceptual structure, not just procedural skills (Johnson & Johnson 1987). To this end, several ways of modelling an expert's psychological profile have been proposed. For example, personal construct psychological theory has been applied through the use of repertory grids which map associations between domain elements and constructs or characteristics (Shaw & Gaines 1987). Gammack (1987) provides a review of techniques for gaining insight into experts' conceptual structures, along with the strengths and weaknesses of various methodologies.

Where experts have difficulty in describing the decision process, computerised rule induction can be employed if documented examples are available. This methodology uses Shannon's (1949) information theory to define the amounts of information within classes of a set of examples defined by records, and results in a decision tree. Induction yielded a decision tree which successfully discriminated 92% of the cases in an independent test set

(Hart 1987). The organisation of a useful training set was not trivial, and the method was successful when carefully monitored, with adjustments to classes in the set. The final decision tree was compiled with the help of an expert, who had previously found thinking abstractly about the decision process to be difficult.

b) Knowledge interpretation. As knowledge is gathered from an expert, it should be interpreted. An attempt has been made to structure the task of knowledge acquisition (Breuker & Wielinga 1987), emphasising the separation of information elicitation from information analysis. A classification was made of epistemological primitives, or types of knowledge, which might be expected in any domain. Once the information was so classified, mapping into appropriate knowledge-representation schemes was easier.

4) Knowledge representation

Several types of knowledge representation schemes have been developed, and these are often used in combination within a program. Representation schemes should be selected after knowledge acquisition, to suit the requirements of any particular domain. Some commonly used schemes include backward chaining, forward chaining, and frames and scripts. Neural nets are beginning to be used more frequently again for some tasks, and theoretical problems with current schemes for uncertainty management have led some developers to explore probabilistic causal diagrams for knowledge representation.

a) Backward chaining. A common rule-based representation, ideally suited to diagnostic programs such as MYCIN (Shortliffe 1976), is backward chaining. Given a logical set of "if/then" rules and facts, the algorithm satisfies a goal through pattern matching in the manner set out below (Parsaye & Chignell 1988).

(i) If the goal is a built-in clause, evaluate it according to the rules specified in the programming language.

(ii) If the goal matches a fact, succeed and return a value of "true".

(iii) Try to match the goal with the conclusion of a rule in the knowledge-base. If there is no matching rule, fail and return "false".

(iv) If a matching rule is found, try to prove each clause in the premise of the rule. If all clauses succeed, return "true".

(v) In performing (iv), above, if a clause fails, go back to the previous clause, and try to find new solutions for that clause, with the hope that these might allow the failed clause to succeed.

(vi) If the rule fails, try the next matching rule in the knowledge-base.

b) Forward chaining. When many rules but few facts are available, forward chaining, a data-directed strategy may be useful. A forward chaining interpreter working in sequence of rule appearance in the knowledge base would use the algorithm described below (Parsaye & Chignell 1988).

(i) Prove the premise of the first (or next) rule in the rule set. If the premise succeeds, add the conclusion to the fact-base.

(ii) Check to see if the hypothesis (if any) has been proved. If so, stop and succeed.

(iii) Repeat (i) and (ii) for all rules in the rule set until all rules have been tried.

(iv) If new assertions have been added to the fact-base, then repeat the cycle from (i), otherwise, stop.

To make the above algorithm more efficient, when a fact is asserted in the fact-base, all rules with the fact as a conclusion should be deleted from the rule-base.

Combinations of forward and backward chaining are also possible (Parsaye & Chignell 1988).

In forestry, a species selection knowledge-based program has been written using forward chaining inference (Rice *et al.* 1989).

c) <u>Frames and scripts</u>. Many advanced knowledge-based programs, especially those where a solution must be constructed (as opposed to being selected), employ frame-based knowledge representation, and a script to define the problem solving procedure (eg: Mittal *et al.* 1986). Rule-based representations are often included in conjunction with frames (Parsaye & Chignell 1988).

Minsky (1975) developed the concept of frames for representing knowledge. Essentially, a frame is a data structure with "slots" which can contain either properties (scalars), or procedural knowledge (vectors). The structure of a frame implies an expected condition.

Frame-based systems usually employ a network of frames in a hierarchy, with lower level frames inheriting attributes and capabilities from higher level frames. This inheritance allows a very efficient representation of knowledge. A script describes what is expected, how expectations should be adapted to reality, what should be done at any stage in design, and in what order the stages should occur.

d) Representation of uncertainty. A decision situation consists of information plus uncertainty. Uncertainty can arise from measurement error, lack of knowledge about particular variables or relations, and "fuzziness" of semantic associations. As knowledge-based programs are often aimed at reducing the uncertainty associated with a decision, representing uncertainty is an important, but often under-emphasised aspect of program development. For dealing with uncertainty, two basic steps have been identified (Parsaye & Chignell 1988):

(i) determining the uncertainty of a basic set of events;

(ii) compounding the values obtained in (i) to arrive at the uncertainty of compound or complex events.

Several alternative ways of coping with uncertainty have been used. In deciding on a representation scheme for MYCIN, Shortliffe (1976) considered and discarded systems based on Shannon's (1949) information theory and Bayesian probability. Maximising the entropy of the set of possible diagnoses required more *a priori* probabilistic information than was commonly available, a requirement shared by information theory and Bayesian probability. The latter also required an assumption that outcomes were disjoint, an event rarely found in diagnostic systems. In addition, use of Bayesian probability would imply that all measures of probability were similarly accurate, which is unlikely when subjective probability is involved (Parsaye & Chignell 1988).

Certainty factors devised by Shortliffe (1976) fitted well with backward chaining inference, allowing the incremental combination of subjective estimates of uncertainty surrounding conclusions in a rule with that of users' replies. Both positive and negative certainty factors were calculated, the latter representing measures of disbelief. The *ad hoc* nature of this scheme has attracted criticism. In order for the backward chaining algorithm to work effectively, it was necessary to specify a level of truth below which a fact could not be used to satisfy a premise. This was set arbitrarily at 0.2. Despite theoretical shortcomings, certainty factors are simple to use, and have been effective in representing uncertainty in many knowledge-based programs.

An alternative approach is to use Dempster-Shafer evidential reasoning (Shafer 1976).

The sum of the probabilities of an assertion and its inverse is allowed to be less than one, and the system allows reasoning about plausibility and belief separately. This may improve the performance of complicated decision systems compared to simpler certainty factors.

To represent uncertainty of semantic associations, such as tallness, or degree of membership in a set (eg: is a vanette a van, a minibus, or a stationwagon?), Zadeh (1965) devised fuzzy set theory and fuzzy logic. In fuzzy set theory, membership of a set is denoted by a number between 0 and 1, implying degrees of membership. Statements in fuzzy logic are associated with a continuum of relative truth values, instead of being absolutely true or false as in Boolean logic.

The type of representation chosen varies with the domain concerned and probably with the prejudices of system developers. There are clearly theoretical problems with most approaches so far devised, and many tools for developing knowledge-based systems allow several alternative systems for managing uncertainty. In the herbicide selection system described here, no representation of uncertainty was required. However, designing regimes covering several seasons would require uncertainty management.

e) Probabilistic causal diagrams. In an attempt to solve some of the theoretical problems inherent in calculating confidence factors, and to avoid problems caused by lack of rule modularity, some developers have begun to explore the use of probabilistic causal diagrams (Kornfeld 1991). These are similar to Bayesian belief networks, except that the associations between nodes are assumed to be causal. For some classes of diagnostic problems, they offer a theoretically sound representation scheme, but the probabilities of various events must be well established beforehand.

f) Neural nets. Neural nets are software or hardware structures which can learn by example, given particular types of problems (Rumelhart *et al.* 1986, Caudill & Butler 1990). They consist of massively interconnected structures known as neurodes, which output a weighted sum of incoming signals. Knowledge is contained in the weights between connections, and these can be taught to the net by a learning scheme known as the Delta rule. Many different types of configurations have been demonstrated, but the most practically useful arrangements appear to be layers of neurodes with information moving from an input layer, through one or more middle layers, to an output layer. The ineffectiveness of 1950 vintage middle layer learning was demonstrated by Minsky & Papert (1969), but this limitation was later removed by the development of backpropagation, an application of the chain rule from Calculus in adjusting the weights of middle layer connections (Rumelhart *et al.* 1986).

Problems suitable for neural nets are those where many historical examples are documented, the inputs and outputs can be expressed numerically, and the logic governing the outcome of the decision process cannot be identified by humans currently making the decision. Neural nets have also been capable of pattern and voice recognition.

Current implementations of neural nets are usually on single processor machines, with the neurodes as software structures. It is expected that multiprocessor machines will be built to represent them in future.

Neural nets were not considered to be appropriate for the knowledge representation reported here, as much of the information was non-numeric. Future forestry systems may exploit the learning capabilities of neural nets, however.

g) Software tools for knowledge-based representation. Traditional procedural software languages such as Fortran, Pascal and Basic could theoretically be used for knowledge-based programs, but developers find that higher-level languages allow more emphasis on and clarity of the logic and knowledge embodied in the system.

Languages which manipulate symbols, such as LISP and PROLOG are often used for rule-based systems (Stock 1987). PROLOG is a declarative language; that is, programmers can write the essential logical elements of a problem, and the language will find answers to queries through a built-in backtracking mechanism (Prolog Development Centre 1990). It has the advantage that a program can be regarded either declaratively or procedurally, a feature which provides exceptional flexibility.

Rule-based shells (see glossary) are also available. The first was EMYCIN, a version of MYCIN with all the specific knowledge removed (Stock 1987). These are often very useful for straight diagnostic problems, but reliance on them can lead developers to constrain knowledge representation to fit shell capability instead of devising representation schemes which properly fit the problems of domains.

Frame representation can be achieved adequately with PROLOG (Jay & Knaus 1989), but most frame-based systems exploit object-oriented programming languages such as

Smalltalk (Digitalk 1991), and C++ (Borland 1990). Object-oriented languages are programmed with hierarchical classes. Classes include attributes and behaviours specific to themselves, and inherit attributes and behaviours from higher level classes. Emphasis is placed on getting "objects" to respond to commands, instead of doing operations *on* objects as in traditional languages.

PROLOG was originally conceived as a language for multi-processor computers, and it is possible that hardware neural nets will be programmed in PROLOG. Software implementations of neural nets on single processor machines are most often written in C, owing to its speed of execution.

Plantation establishment technology includes many non-numerical representations, and knowledge-based programming will become increasingly important as a means of clarifying, permanently recording, and using this knowledge. Whilst many of the techniques described here have been successfully employed in forestry (Mason 1991b), they are likely to be combined with numerical representations, especially growth and yield modelling in order to create effective decision-support systems.

II.3. GROWTH MODELLING

Traditionally, making decisions about plantation establishment in New Zealand has involved estimates of the effects of treatments derived from local experience. There is clearly a need for quantitative estimates of the effects on crop performance of alternative establishment strategies and these might be obtained from numerical models. Growth and yield modelling of stands after successful establishment has been common, and the development of modelling techniques is reviewed below.

1) Yield tables

Early attempts to model stand productivity of even-aged forest crops were aimed at predicting yields per unit area obtainable from "fully stocked stands" in a region or from a particular type of site at different ages. To this end, normal yield tables were generally constructed by graphical techniques using data from temporary plots (Bruce 1926). Assessment of normality (or full stocking) was essentially subjective, and it was recognised that most stands encountered were less than fully stocked.

Empirical yield tables attempted to characterise the expected yield from stands with average stocking, based on random samples from stands of different ages (Husch *et al.* 1972). This approach was more objective than that used for normal yield table construction, but the resulting tables were insensitive to variation in stand density.

2) Density

Stand density reflects the extent to which trees use a site. At any given age, density in an unthinned stand might be expressed as stems per hectare, but measures which relate numbers of stems to average tree size are generally more independent of age and site quality.

Reineke (1933) defined stand density indices as linear relationships between the logarithm of stems per unit area and the logarithm of mean dbhob with functional parameters that varied slightly for different species. This implied a limiting relationship between average size and stocking. A similar assumption was implied by the use of tree area ratio (Chisman & Schumacher 1940), where the area occupied by a given tree in a fully stocked stand was expressed as a quadratic function of dbhob.

Relative spacing, the ratio between average distance between trees and average height of the dominant stems, has also been used successfully to represent density (Beekhuis 1966).

Measures of stand density commonly used in modern growth models are basal area per unit area (the sum of stem crossectional areas at breast height, usually derived from measures of dbhob), and numbers of stems per unit area.

Garcia (1984, 1990) and West *et al.* (1982) used representations of tree canopy as measures of density. In the former case, canopy closure was derived from levels of thinning and pruning of stands assumed to have 100% closure, whilst in the latter, the total length of crown per hectare was directly estimated from tree height, pruned height, and numbers of stems per hectare. These models were built to fill a need for more sensitive characterisation of growth and yield in heavily thinned and pruned stands of radiata pine in New Zealand.

Stand density measurement allowed the production of yield tables sensitive to stand density (MacKinney *et al.* 1937), known as variable density yield tables. MacKinney *et al.* (1937) also improved on graphical techniques by using least-squares regression to estimate parameters of functionalised yield curves. Variable density yield tables for radiata pine in New Zealand were prepared using graphical techniques by Lewis (1954).

3) Representation of site fertility

Most yield prediction systems represent fertility as a function of observed tree growth directly, with regional models, site quality classes, and/or site indices.

Early yield tables in New Zealand were regional (Lewis 1954), prepared for specific administrative requirements in local areas. There is still a tendency to regionalise growth and yield models, where regions are associated with marked differences in climatic or soil characteristics, requiring markedly different shapes of site index functions (Burkhart & Tennent 1977, Garcia 1983). While this can be an economical way to deal with site differences, such systems imply that moving from one region to another immediately results in a fundamental change in shape of yield curves, a most unlikely event in reality, and one that can sometimes lead to inconsistency of prediction (Whyte *et al.* 1992). Moreover, representing site variation by means of site index does little to identify the reasons for that variation.

Site quality classes representing the productivity of *Pinus radiata* are still used in South Australia, where productivity varies markedly within regions, and is associated with varying soil qualities and rainfall (Boardman 1988).

The most often-used representation of site productivity is site index, where sets of related height over age curves are created from repeated plot measurements over a region. The index number for any given site is the expected mean top height at a constant age. In New Zealand, this is commonly used for growth and yield models of *Pinus radiata* (Lewis 1954, Beekhuis 1966, Burkhart & Tennent 1977, Garcia 1983). Height growth of dominant and codominant trees is generally independent of stocking (Assmann 1970, Lanner 1985), and environmental variables which might be expected to cause growth differences (such as precipitation, temperatures, soil nutrition and soil drainage) are rarely available to managers, hence this representation of site quality is very convenient. There are several possible limitations of the methodology, however:

(i) environmental factors influencing growth are not specifically included in the modelling system, leading to limited understanding and model inaccuracy if these factors change;

(ii) height is usually measured with less precision than other stand state variables such as basal area/ha;

(iii) variations in height growth may not always be directly related to variations in volume growth if basal area growth is differently influenced by factors affecting growth.

An example of the first limitation is changing trends identified in mortality of radiata pine in the Central North Island region over the last 30 years (Klitscher 1987). Control of *Sirex* and *Dothistroma* outbreaks, improved genotypes, and improved management practices were proposed as reasons for the changes in trends, but the causes have never been definitively identified.

Representations of site quality indirectly related to the crop species include the use of "indicator species", and the prediction of fertility from environmental variables. Ure (1950) related site productivity in Kaingaroa Forest to the presence or absence of certain understorey plant species.

Jackson & Gifford (1974) found that seven year periodic volume growth in fully stocked stands of *Pinus radiata* on level sites with adequate nutrition in New Zealand was related to mean annual precipitation, seasonal rainfall distribution, effective soil depth, total nitrogen, available (Olsen) phosphorus, seasonal departures from postulated optima night (5°C) and day (20°C) temperatures, and several of their interactions. Similarly, site index of radiata pine in the North Island of New Zealand has been related to mean annual rainfall and temperature at the closest meteorological stations, soil nutrients, topsoil depth, soil penetrability, and soil pH (Hunter & Gibson 1984).

4) Growth and Yield

A significant advance in growth modelling was the use of compatible growth and yield functions with growth as a derivative of yield. Clutter (1963) estimated parameters for a compatible growth and yield system using data from permanent sample plots by means of difference equations, expressing future yield as a function of existing yield and the change in time. Difference equations can be derived for any growth and yield system by separating the yield and time variables in the derivative, and then integrating each side of the equation from T_1 to T_2 and from Y_1 to Y_2 respectively.

Clutter *et al.* (1983) noted several desirable properties of functions used for growth and yield models:

(i) representations of growth and yield should be compatible;

(ii) the functions should be consistent, i.e. as T_2 approaches T_1, Y_2 should approach Y_1;

(iii) they should be path-invariant, i.e. predicting Y_3 from Y_1 should yield the same answer as predicting Y_2 from Y_1 followed by Y_3 from Y_2;

(iv) as T_2 approaches ∞, Y_2 should approach an upper asymptote.

Most yield prediction systems nowadays comprise functions with these properties.

5) Common features of stand level models

Models of growth and yield of forest stands generally have several features in common.

a) Components. It is common for modellers to adopt at least a three-dimensional state description, comprising height, basal area, and numbers of stems per unit area, so that to a reasonable level of accuracy, future states of the stand can be determined by the current state and future actions (Garcia 1988). Modelling systems also usually include some characterisation of tree form and volume, but growth is usually not a direct function of these variables. Often height is used as a representation of site quality, through site index, and basal area and stems per unit area are the primary representations of density. Predicting growth in basal area is usually the key to predicting future yields. In addition, mortality functions represent the decline in numbers of stems per hectare over time.

b) Functions used. Sigmoid functions are commonly used to represent height and basal area yields, along with inverse sigmoid functions for mortality. Clutter (1963) used a function relating the natural logarithm of yield to the inverse of time first proposed by Schumacher (1939). Other sigmoid forms are often used (Woollons & Wood 1992), such as the Weibull, Gompertz, Hossfeld, and the Von Bertalanffy-Richards (Von Bertalanffy 1957, Richards 1959). This last function is particularly malleable, as it is a generalised form of the Gompertz, Monomolecular and Autocatalytic functions (Richards 1959), but parameter estimation can be difficult because the parameters tend to be highly correlated (Woollons & Wood 1992).

c) Estimation of parameters. Clutter (1963) used non-linear least-squares for parameter estimation, and researchers still frequently use the same technique. Garcia (1983, 1988) identified potential problems with this technique because:

(i) there were correlations between repeated measurements from permanent sample plots, although increments would be more nearly independent;

(ii) the dependent variables (height, basal area and numbers of stems per unit area) were often correlated;

(iii) the increments from repeated measurements often contained varying differences in time.

The solution Garcia proposed was to simultaneously estimate parameters for integrated forms of all functions in the modelling system by means of stochastic maximum likelihood. Variation from the model was assumed to be a Weiner process, that is the expected deviation was related to the square root of elapsed time. The importance of these potential problems with least- squares estimators has not been widely supported however. Sullivan and Clutter (1972) compared least-squares estimation with maximum likelihood for growth and yield modelling and reported that there were no differences of practical importance in the values of estimated parameters. Joint estimation also restricts the choice of functional form for the individual state variables.

Lack of independence between measurements from a permanent sample plot means that commonly used measures of goodness of fit such as R^2 and the residual mean square are of limited value when least-squares estimation is employed. Modellers should focus instead on the normality of residual distributions, the range of residuals, and lack of residual bias in relation to predictions and independent variables.

d) Validation. After growth and yield models have been constructed, they should be validated to ensure that they provide useful inferences about the growth of stands. Three stages in validation have been identified (Goulding 1979):

(i) evaluation of the model to ensure that it conforms to currently understood features of the modelled system, and has been properly constructed;

(ii) verification of the logic and arithmetic embodied within the computer program;

(iii) comparison of model projections with independent measurements of the modelled system under a variety of initial conditions.

A model cannot be proved true, rather, it is accepted that models are approximations of reality, and the objective of a validation procedure should be to identify conditions in which the model can be usefully employed with confidence, as well as those circumstances where the model would be either inaccurate or too imprecise to be useful. It is expected that validation of the initial growth models described here will include all three stages, although stage (iii) will be somewhat limited because of small amounts of independent data.

6) Models as functions of height

Beekhuis (1966) built a model of the growth of radiata pine in New Zealand in which height was used as a dependent variable for basal area and mortality functions instead of time.

Similar models have been constructed by Garcia (1984, 1990) for radiata pine in New Zealand, and Harrison & Daniels (1988) for loblolly pine in the Southern United States in which estimation of parameters involved the use of time adjusted to a common site index. This implied an assumption that allometric relationships within stands were independent of site quality. Whilst this assumption might be adequate for growth and yield projection purposes in many instances, there is some evidence of differences in responses of height and diameter to varying environmental conditions; for instance, where weed competition is a factor in determining site quality (Zutter *et al.* 1986, Richardson 1991), or where seasonal droughts are responsible for reductions in productivity (Jackson *et al.* 1976).

Whilst many stand level models have been constructed, managers are generally interested in knowing what range of bole sizes could be harvested from stands at different ages. Several means of representing individual tree sizes have been devised, including individual tree models, and size distribution models.

7) Individual tree models

Forest growth models have been classified as whole stand, distance-independent individual tree, and distance-dependent individual tree (Munro 1974). Distance-dependent models use distances to adjacent trees as independent variables for predicting the growth of individual trees, while distance independent ones ignore distances to adjacent trees when making predictions for individual trees. Individual tree models are generally employed when stand structure is so irregular that density cannot be reasonably described by a single measure for the entire stand (Bruce & Wensel 1987). A distance-independent individual tree model was used to characterise uneven-aged, mixed species stands (Stage 1973). Individual tree growth models have been constructed for radiata pine in New Zealand, both distance-dependent (Tennent 1981), and distance-independent (Manley 1981).

Bruce & Wensel (1987) identified two costs of using a more complicated model than necessary:

(i) greater computational expense;

(ii) loss of precision in estimates.

In even-aged plantations of radiata pine, managers tend to prefer stand-level models to individual tree models, and, given the regularity of most stands, this would appear to be a wise preference.

There is an alternative to individual tree models for characterising tree sizes; distribution models.

8) Distribution models

Distribution models represent the relative frequencies of trees of different sizes within an even-aged stand by means of a distribution. Early attempts employed the Gamma distribution (Nelson 1964) and the Lognormal distribution (Bliss & Reinker 1964) to describe frequencies of diameters.

The Weibull probability density function was first employed by Bailey & Dell (1973), who pointed out that it was flexible, simple, and had a closed form, simplifying calculation of diameter class frequencies. Estimation of parameters was achieved by percentile estimators, as functions of mean stand statistics. In New Zealand, the most often-used modelling system for radiata pine predicts log size distributions from a Weibull function with parameters estimated directly from mean stand statistics (Goulding 1986).

A 3 parameter Weibull distribution was used to represent *Liriodendron tulipifera* diameter frequencies, with the minimum diameter estimated independently, and other parameters recovered from stand models (Knoebel *et al.* 1986). Knoebel & Burkhart (1991) found that distribution parameter prediction methods were inferior to either percentile estimators or parameter recovery techniques. The latter group involves the recovery of Weibull distribution parameters from models of basal area/ha, dbhob variance, and maximum dbhob, and results in compatible basal area and distribution models (Hyink & Moser 1983).

Recent research has shown that using the maximum diameter as a location parameter for a reverse Weibull distribution is a more effective way of representing diameters than using the minimum diameter, because it shows a stronger relationship with time (Kuru *et al.* 1991). The extreme value distribution was used to adjust maximum estimates for douglas fir plot size (Liu Xu *et al.* 1992), and the system has worked well for Carribean pine (Villanueva & Whyte 1992).

Although the Weibull is computationally convenient, and reasonably effective at representing diameter distributions, it has a limited range of skewness and kurtosis. Hafley

& Shreuder (1977) proposed that modellers use the Johnson S_B distribution (Johnson 1949b), as it can represent a wider range of skewness and kurtosis. Comparisons of the Johnson S_B with the Weibull, Lognormal, Gamma, & Normal distributions showed that it provided a better fit to dbhob data from 21 stands. A bivariate form, the Johnson S_{BB} (Johnson 1949a), has been used to map existing distributions on to future ones, although some work is needed to sort out the implications of mortality in such a modelling system (Knoebel & Burkhart 1991).

There are apparently insuperable theoretical problems with diameter distribution and individual tree models (Garcia 1991). Correlations between trees due to site variation, and competition between adjacent trees mean that dbhob variance varies with stand (or plot) size. Whyte & Woollons (1992) suggest that better coordination of crop inventory, growth modelling, and yield forecasting should provide a solution to the problem. If growth models are constructed from plots of similar size to those used for inventory, and inventory plot means and distributions are projected forward for yield forecasting purposes, then future distribution estimates should be consistent with those obtained from future inventories in the stand. It is interesting to note that, as mean top height is generally estimated from trees in an upper portion of the distribution of diameters, it may also be biased with plot size. The practical importance of any such bias has not been evaluated.

Given the need for simple, practical models, and the usefulness of tree size-class information, a distribution model of radiata pine during the establishment phase was considered ideal.

9) Biological basis of growth and yield models

The success of stand-level growth and yield modelling arises from a consideration of a stand as an ecological entity with an ability to use an area of land which can be estimated from stand dimensions. Clearly, limitations of space for crowns and roots, and root grafting make this representation logical, but it is useful to consider what deeper biological basis lies behind the forms which such models often take.

a) Sigmoid curves. Sigmoid curves have been used to represent the yield of many biological growth processes (Causton 1983), and result from a consideration of growth relative to existing organism or population size, or "relative growth rate". A sigmoid yield curve arises from a variation in relative growth rate with time. If growth were a simple function of size, then the yield curve would be exponential.

A sigmoid growth curve proposed by Von Bertalanffy (1957) is derived by considering growth as the difference between anabolic and catabolic processes, with anabolic processes some function of organism surface area, while catabolic processes are a function of organism volume. For animal growth, such an hypothesis can be justified, and it is proposed as a justification for the use of the curve in some forest growth and yield models (eg: Somers & Farrar 1991). However, Richards (1959) explored the function, and pointed out that some of the most useful forms contained parameter estimates which were inconsistent with Von Bertalanffy's hypothesis. In any event, many of the most valuable parts of trees, especially heartwood, contribute little to catabolism, so representations of respiration as a function of total tree biomass are likely to be incorrect.

Plant dry matter production is generally a linear function of intercepted radiation (eg: Monteith 1977, Biscoe & Gallagher 1975). The same relationship has been reported for radiata pine in New Zealand (Grace *et al.* 1987); intercepted radiation increased with increasing amounts of foliage, at least up to a leaf area index (LAI) of 3.5. Hunter *et al.* (1987) found annual radiata pine bole volume increment/ha was linearly related to foliage mass and percentage foliar nitrogen. At some maximum LAI, the canopy can be considered "closed". For agricultural crops, LAI values greater than 4 were considered to represent a closed canopy (Biscoe & Gallagher 1975). However, for Radiata pine above-ground production was found to increase approximately linearly with LAI values as high as 10, and showed a declining rate of increase up to LAI values of 20 or more in unthinned stands (Beets & Pollock 1987).

Increases in plant dimensions prior to canopy closure (immediately after plantation establishment, or after thinning or pruning), might therefore be expected to follow an exponential function. This would be due in part to correlations between sizes of different parts of a growing plant, known as "allometric relationships".

Growth in plant biomass should be the difference between matter created by photosynthesis and that consumed by respiration. Measurements of radiata pine stand respiration rate show a linear correlation with rate of photosynthesis (Beets pers. comm.). This might be expected given that the surfaces involved in absorbtion of nutrients and production of photosynthate (fine roots and needles) are also those most involved with respiration, and their total volumes and surface areas might be expected to be related linearly. This latter relationship is due to the approximately constant sizes of these parts, with increases in total volume or surface area related directly to their number. It should be noted, however, that the specific leaf area of radiata pine needles has been reported to decrease by more than 20% between tree ages 2 and 12, with most of the decrease occurring prior to age 8 (Beets & Lane 1987), therefore LAI cannot be considered to be completely equivalent to foliage biomass at different ages.

After a forest canopy has closed, one might therefore expect the growth rate should no longer increase, and that, given no changes in foliage efficiency or foliage carrying capacity, that biomass growth should be roughly linear over time. Foliage mass of radiata pine was reported to increase with age until an equilibrium level was reached (Madgwick *et al.* 1977), and the same was reported for Douglas fir (Long & Smith 1984). Not all crops exhibit this pattern of foliage mass with time, however; Switzer *et al.* (1968) found that *Pinus taeda* stand foliage increased to a maximum, then declined to a reasonably high equilibrium level, while that of *Betula spp.* increased to a maximum which was also the equilibrium. Kuuluvainen (1991) found that foliage in a naturally regenerated stand of *Pinus sylvestris* increased with time to a maximum, and then declined sharply. The current annual increment of bole volume peaked before the time of maximum foliage. Kuuluvainen suggested that the decline in foliage and growth was due to competition stress, immobilisation of nutrients, and more mutual shading of trees as stocking diminished. Beets & Pollock (1987) found that radiata pine LAI increased with age to a maximum at age 6, and then declined.

Models of radiata pine stand growth and yield in New Zealand show stands exhibiting exponential bole volume growth initially, or after thinning, with yields subsequently increasing roughly linearly with age, at least up to age 30 (Garcia 1984, 1990). However, this linearity cannot be entirely attributed to constant total biomass growth after canopies have closed, because partitioning of dry matter has been found to change with physiological age in studies of radiata pine aged between 2 and 12 years (Beets & Pollock 1987). Total above-ground production at a given LAI was found to increase with age, and this was attributed to a shift in partitioning from roots to stem wood. In addition, relatively more dry matter production was invested in stem wood than leaves as stands aged.

It is highly likely that radiata pine would exhibit a similar decline in growth to that described by Kuuluvainen (1991) at ages exceeding usual rotation lengths in New Zealand, and that this would be caused in part by physiological age. In addition to the results reported by Beets & Pollock, time-dependent changes in crown characteristics associated individual young tree growth rate have been clearly demonstrated using cuttings (Menzies *et al.* 1991). The biochemical processes causing physiological aging are not well understood.

In summary, as a working hypothesis, sigmoid yield curves are appropriate in stand growth and yield models because stands increase in growth rate as a function of their increasing occupation of land area, and then reach maximum growth with the foliage carrying capacity of the stand. Leaf biomass may peak and then decline, or may possibly remain at equilibrium for a period of time. Subsequently, for poorly understood reasons, aging results in a decline in LAI and growth rate. For New Zealand radiata pine stands, at least in the Central North Island and Nelson regions, stand growth of stem volume is initially exponential, and then approximately linear within usual rotation ages, possibly because, despite an overall decline in production with decreasing LAI, relatively more carbon is allocated to stems with age. Sigmoid basal area per hectare yield curves are appropriate in this latter case, because basal area/ha is a fractional power of volume.

It is clearly relevant as a follow-up to the material just reviewed, to consider what factors determine the foliage carrying capacities of stands.

b) Foliage carrying capacity and foliage efficiency. Foliage carrying capacities of stands may be related to site quality. Radiata pine suffering from nutrient deficiencies commonly carries visibly less foliage than it does with adequate nutrient supplies (Will 1985). Increases in foliage mass were associated with growth responses to fertilisation (Waring 1974, Mead *et al.* 1984).

Site can also affect the relative efficiencies of foliage by affecting the lengths of growing seasons, as a result of seasonal changes in day length, temperature and/or water supply (Jackson & Gifford 1974).

The level of foliage in fully closed, even-aged Douglas fir stands was independent of density, but the rate of approach to an equilibrium foliage level was proportional to density (Long & Smith 1984). It has often been suggested that foliage level is related to the crossectional area of the sapwood "pipe" supplying water to the canopy (eg: Harrison & Daniels 1988), and this would be consistent with the suggested relationship between density and rate of approach to equilibrium. The proportion of sapwood measured in cores taken from radiata pines growing on a wide range of sites in New Zealand decreased with tree age (Cown *et al.* 1991). It may not be coincidental that heartwood development was found to begin between ages 5 and 8, when LAI would have reached a maximum.

Measurements of foliage mass in radiata pine stands between ages 6 and 22 in Kaingaroa forest showed that foliage mass was independent of density at stockings greater than 400 stems/ha., but diminished with diminishing stocking below this level (Madgwick *et al.* 1977). This is consistent with the behaviour of model PPM88 (Garcia 1990), where the difference in bole growth rate between stands of 100 stems/ha. and 200 stems/ha. is as great as that between 200 stems/ha. and 500 stems/ha..

It is interesting to note that most of the discussion about optimum final crop stockings for radiata pine in New Zealand focuses on stockings between 200 and 400 stems/ha., the range in which foliage mass after closure might be expected to vary with stocking. Whyte & Woollons (1990) reported that, in a thinning experiment in Kaingaroa Forest, yield from a stand thinned to 300 stems/ha was so much greater than that of a stand at 200 stems/ha, that volumes of the largest 200 trees/ha in the 300 stems/ha plots were almost as great as the entire yield from plots thinned to 200 stems/ha.

Foliage carrying capacities also differ markedly between species (Madgwick *et al.* 1977).

In order to represent thinning and pruning effects in models of radiata pine, researchers have found estimates of remaining foliage to be very useful, either as kilometres of crown/ha. (West *et al.* 1982), or as percentage canopy closure (Garcia 1990).

Immediately after establishment, as seedlings grow without between-tree competition, one might expect that biomass production should be a function of plant size, and that, given the allometric properties of stands, exponential functions should accurately represent mean height and basal area/ha.

In addition to stand basal area, volume, and height, managers are also interested in mortality occurring in stands, and several researchers have proposed biological mechanisms to explain how mortality should be modelled.

c) The -3/2 "law". A geometrical appraisal of growth processes in agricultural crops has led to a "law" of stand density which is actually a hypothesis of a power relationship between numbers of plants per unit area, and average plant mass. As explained by Drew & Flewelling (1977), given certain assumptions, mean plant weight should be directly proportional to plants per unit area to the -3/2 power. Assuming a proportionality between mean tree weight and dbhob to the 5/2 power, this weight and stocking relationship is equivalent to Reineke's (1933) stand density index.

There is some evidence that the relationship might be applied to New Zealand's radiata pine crops (Drew & Flewelling 1977), but Zeide (1987) points out that two necessary assumptions required by the so-called "law":

(i) complete canopy closure is maintained by the combined action of crown growth and self-thinning;

(ii) plants of the same species are always allometrically identical;

are usually untenable. The area of gaps in canopies created by mortality might be expected to increase with stand age, and the crown weight:crown length ratios of trees were found to decline with age. Careful analysis of data from long-term permanent sample plots indicated that the hypothesised log-log line was in fact a curve. Reineke's (1933) use of stocking in relation to dbhob was found to be more reliable, as dbhob was more closely related to crown dimensions than was plant mass. Although Reineke's power constant was found to be -1.605 for 12 of 14 species, it has been found to vary with other species (Zeide 1987).

As a generalised hypothesis, the decline in plant number with increasing average plant size justifies the frequent use of polymorphic mortality functions in stands where between-tree competition is occurring. However, the use of only two parameters, one being the universal -3/2 constant, appears to be an over-simplification of the process. Models of stand growth and yield with higher resolution will require more refined representations of allometric relationships and competition.

In the studies reported here, anamorphic mortality functions should be more appropriate, as little between-tree competition occurs immediately after establishment.

d) Differing resolutions of models. Munro (1974) proposed a major difference between analytic and empirical growth models, sometimes known as process and empirical models (Bruce & Wensel 1987), or functional and predictive models (Draper & Smith 1981). These distinctions suggest that some models explain processes, whilst others simply represent statistics. As the discussion above shows, growth and yield models, generally regarded as empirical (Bruce & Wensel 1987), represent a growth process, and imply certain properties of the nature of the process. Landsberg (1981) suggests that the distinction between process and empirical models is spurious, and prefers a classification based on temporal resolution with four classes:

(i) minutes to hours;

(ii) hours to days;

(iii) days to weeks;

(iv) seasons.

Without resorting to categories, the resolution of a model can be considered as a point within a 3 dimensional space defined by resolutions in crop dimensions/characteristics, site qualities, and time. The resolution obtained by any particular model will be determined by three factors:

(i) the types of predictions users wish to make with the model;

(ii) the level of understanding of the processes involved;

(iii) the access which users have to relevant independent variables.

Increasingly, forest managers are asking for a greater variety of information from models than simply regional representations of yield. Recent focus in New Zealand has been on the extent and timing of manipulation of crop dimensions by thinning and pruning, resulting in models with better temporal and crop dimensional resolution (West *et al.* 1982, Garcia 1990). Improvements in genetics, increased emphasis on cost-effectiveness of site preparation, changing levels of pathogens such as *Sirex spp.*, and concern about climate change and other environmental issues have prompted managers to ask questions of growth and yield models which exceed their current levels of resolution.

Improved understanding of processes is an important prerequisite to the development of models with appropriate resolution. Jarvis (1981) listed the submodels required for an explanation of stand growth, including models of leaf phenology, radiation interception, stomatal and canopy conductance, photosynthesis, transpiration, carbon allocation, respiration, evaporation, plant and soil water status, plant and soil nutrient status, branch and stem growth, fine root growth, coarse root growth, and population development. A process model at a similar level of resolution to that defined by Jarvis has been built for individual two-year old Douglas fir seedlings (Webb 1991), but it is clear that construction of such a model at a stand level is some way off. Agren (1981) concluded that stand-level physiological models were not yet feasible, and that research should focus on sub-models of processes. Considerable progress was made towards developing a process model of radiata pine at one site in the Central North Island region of New Zealand (the main results were reported in a special issue of the New Zealand Journal of Forestry Science, No. 17 (2/3) in 1987).

A distinction can be drawn between research aimed at stand-level models comprising the results of individual process studies (a bottom up approach), and that which begins with functional stand-level models and seeks to add resolution (a top down approach). Landsberg (1981) concluded that a top down approach may be preferable.

Improved access to independent variables may be provided by geographic information systems. Given the power of these packages to index diverse information on points in space, managers will have more detailed environmental and crop information relating to specific stands than ever before.

Models of the establishment phase should supply answers to a variety of questions about the results of differing nursery, tree handling, and site management practices on crop performance, and therefore require higher levels of resolution in the three dimensions of crop characteristics, site characteristics, and time than have been usual in traditional growth and yield models. A top-down approach to increasing model resolution should ensure that models become only as complex as necessary, and that successive model developments are immediately of use to managers.

10) Initial growth modelling

Payandeh (1987) identified three phases of plantation establishment:

(i) stock production;

(ii) storage;

(iii) plantation (site) management.

Models were created of height and tree survival over time for *Picea mariana*, *Picea glauca*, and *Pinus banksiana* in Ontario, Canada, which were sensitive to genotype (plus tree/unimproved), stock type (container/bareroot), container size, storage (yes/no), site class, site preparation (mechanical/chemical/prescribed burn), planting season, planting method (manual/mechanical), and weed control (yes/no). The models were exponential, as would be expected of growth prior to between tree competition, and separate functions were fitted for each species/stocktype/storage combination. The functions were incorporated into a computer program which calculated a "regeneration cost efficiency index" (RCEI) for each alternative establishment regime for any given site. The index consisted of the cost divided by average plantation height, survival rate and a quality index at the end of the regeneration period (up to 20 years, selected by users). The top five strategies were listed in order of efficiency. While the models were an excellent start to representation of a complicated system, the RCEI implies relative rotation-length advantages due to survival, growth and form which may bear little resemblance to their real relative values.

Payandeh (1987) concluded that improvements were needed in representations of seedling quality, stock types, site preparation, and weed competition/control.

A similar modelling approach was used to represent the survival and height growth of *Pinus resinosa* and *Picea glauca* for the five years following planting in the Great Lakes region of the United States of America (Belli 1987, Belli & Ek 1988). Separate models were fitted to different combinations of species/seedling age at planting (3-0/2-2/2-1)/site harvest history (old field/cutover)/site preparation (cultivate/furrow/ scalp). In addition, the models included adjustments for survival and growth losses due to delays in spring lifting and planting. Measures of establishment efficiency in terms of cost/surviving tree and cost/1000 cm of aggregate height growth were found to give different rankings of alternative establishment strategies.

In a review of the potential for regeneration modelling, Rasenen (1987) suggested that expert system technology would be a useful adjunct to quantitative modelling. A suitable decision-support system should comprise both quantitative and qualitative models.

Many aspects of growth and yield modelling reviewed above cannot be included directly in the studies reported here. It is important, however, to understand current growth and yield modelling techniques fully, because the value of establishment treatments can often only be properly evaluated over an entire crop rotation. The insights gained into the biological basis of growth and yield modelling have a special significance, because effective predictions of effects of establishment treatments over the length of a crop rotation are likely to result from models with higher definition of site and crop interactions than current growth and yield models commonly have.

Decision support systems for forest plantation establishment will contain aspects of the three topics reviewed here - establishment systems, growth modelling, and knowledge-based programming. Establishment systems are complicated, and a useful categorisation of the many important factors involved was given in Figure II.2. Representing this system will require methods developed for both knowledge-based programming, and growth and yield modelling. Quantitive modelling of initial growth, in particular, requires extensions to growth and yield modelling theory; this is discussed in the next chapter.

CHAPTER III

THEORETICAL ASPECTS OF MODELLING INITIAL GROWTH

Growth prior to crown closure has certain unique features which may require representations somewhat different from those commonly employed in growth and yield models for older crops:

(i) there may be little competition between trees prior to canopy closure at the initial spacings commonly employed in New Zealand's radiata pine plantations;

(ii) initial tree size is independent of site quality;

(iii) there are often large effects of microsites on growth;

(iv) the microsites are easily changed through site preparation;

(v) treatments applied to trees prior to planting can have a significant effect on initial growth;

(vi) early growth of crops is concerned with processes before current annual increment curves peak, whereas later growth models are more usually associated with periods after it has peaked.

(vii) dbhob is undefined for young trees less than 1.40 m in height.

Item (i) was a conjecture, and needed further investigation. The analysis of early data from Nelder design spacing experiments described in chapter IV aimed to do so.

Given the differences listed above, it was pertinent to consider what functional forms were likely to be useful for initial growth modelling, from a theoretical perspective.

III.1 MORTALITY

In the absence of specific information about each tree, mortality of trees which are not competing might be considered as a random process in time, and should therefore follow a Poisson probability density function, derived from:

$$\frac{dN/dT}{N}=K \tag{III.1}$$

where K is a constant.

However, freshly planted seedlings may be less likely to die as time passes. This would be due to two influences:

(i) the act of transplanting seedlings from nurseries to field sites can cause stress which results in mortality shortly after planting;

(ii) the range of temperature and likely competition from weeds are more severe for trees close to ground level, and these factors may result in less mortality as trees increase in size.

The constant K would therefore change with time:

$$\frac{dN/dT}{N} = \alpha T^{\beta} \tag{III.2}$$

When solved, this expression results in a Weibull probability density function. The functional form should be anamorphic, as deaths would be independent of stocking.

The survival function used in the Lake States by Belli (1987) was one of exponential decay, of the form:

$$S_T = 100e^{-\alpha T^{\beta}} \tag{III.3}$$

where S_T=survival percentage at the end of year T. Converting this function to a representation of mortality (M_T):

$$M_T = 100(1 - e^{-\alpha T^{\beta}}) \tag{III.4}$$

and taking the derivative, gives a Weibull probability density function:

$$M_T' = \alpha \beta T^{\beta-1} e^{-\alpha T^{\beta}} \tag{III.5}$$

In all but one case, Belli found ß to be less than one, indicating a decline in mortality with time.

It might be expected that α and ß should vary with seedling quality and site quality. Belli (1987) identified different parameters for different site preparation techniques, but multiplied each function by a factor dependent on delays in planting or length of storage. The rationale for this difference in representation between seedling quality and site quality was not clear.

The survival function employed by Payandeh (1987) was similar, but lacked a parameter denoting the power of time, resulting in a less malleable function. Dummy variables denoting effects of site preparation, weed control, stock type, transplanting delay, container size and planting season were linearly related to the α parameter.

III.2 HEIGHT

Prior to canopy closure, one might expect that growth should be exponential, with larger trees having greater leaf and root surface areas. A malleable exponential growth function would be:

$$\frac{d\bar{h}}{dT}=\gamma\bar{h}^{\delta} \tag{III.6}$$

Solving III.6 leads to:

$$\bar{h}_T=\bar{h}_0+\alpha T^{\beta} \tag{III.7}$$

where:

$$\alpha=((1-\delta)\gamma)^{\frac{1}{1-\delta}} \qquad \beta=\frac{1}{1-\delta} \tag{III.8}$$

Equation III.7 was used for modelling mean heights of young conifers in the Lake states (Belli 1987, Belli & Ek 1988). Separate models were estimated for different species and site preparation treatments.

It may be feasible to express the parameters of equation III.7 as linear functions of site preparation dummy variables and their interactions, thus fitting one model to data from a range of treatments. Variables representing site quality prior to treatment might be similarly included. This would lead to a conceptual model different from that shown in Figure II.1, with stand state prior to first thinning as a function of pre-treatment site quality, site preparation, and their interactions (Figure III.1). Using site state prior to modification in this way avoids the necessity of measuring the actual changes in site state brought about by site preparation.

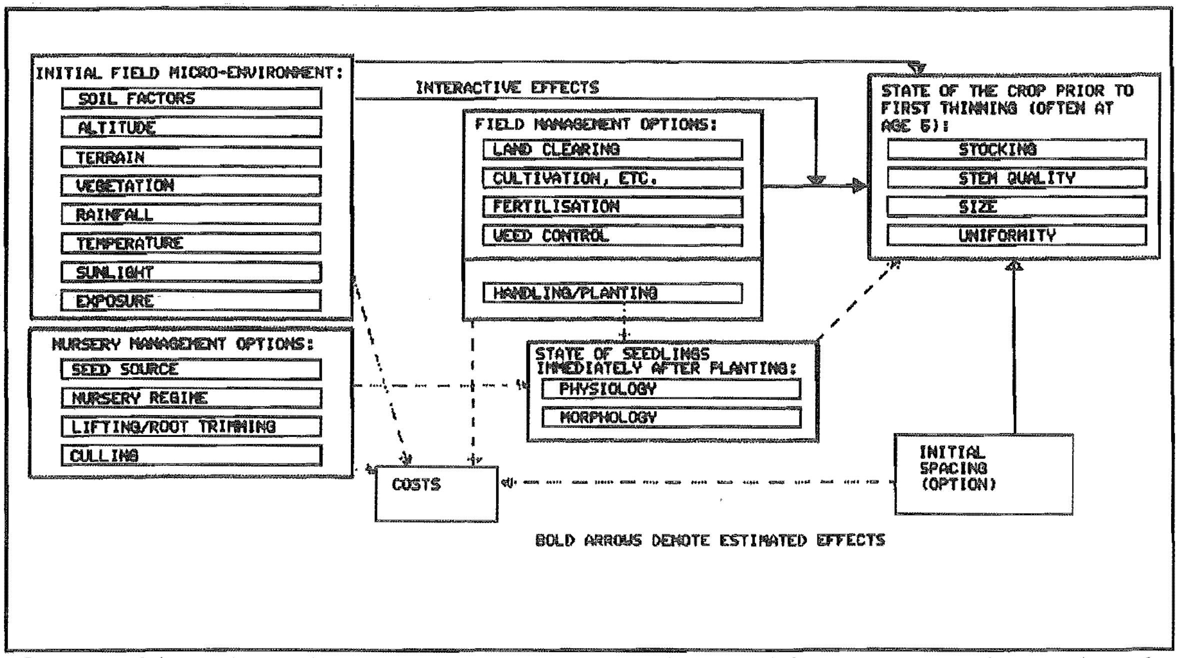

Figure III.1 - A revised conceptual model of establishment compatible with the information in the available database

III.3 BASAL AREA

Dbhob and basal area are undefined for trees with heights less than 1.40 m, and this leads to some interesting theoretical considerations. Basal area was not modelled by other initial growth modellers (Payandeh 1987, Belli 1987, Belli & Ek 1988). Traditionally, as explained in Chapter II, stand basal area has been considered as a useful measure of density in growth and yield models. Basal area growth can be considered as a function of basal area plus a "relative growth modifier (RGM)" which transforms the function from an exponential to a sigmoid:

$$\frac{dG}{dT}=f(G,RGM) \tag{III.9}$$

Such functions exploit the allometric relations between basal area and growth surfaces of stands (such as leaf surface area), and imply that if:

$$\textit{then:} \quad \begin{aligned} &G=0 \\ &\frac{dG}{dT}=0 \end{aligned} \tag{III.10}$$

This condition is clearly untrue, because at G=0, trees in the stand have considerable leaf and root surface areas, and grow quite rapidly through the point where height = 1.40 m. One would therefore expect that basal area growth would be underestimated at times when basal area is close to 0 (see chapter IV for an illustration of this).

A possible solution to this difficulty is to represent basal area growth as a function of basal area plus k:

$$\frac{dG}{dT}=f((G+k),RGM) \tag{III.11}$$

where k represents the allometric capacity of the stand to grow when G=0. Using this methodology, a modified Gompertz basal area function used by Whyte & Woollons (1990) would become:

$$\frac{dG}{dT}=(G+k)(-\beta\ln(\gamma)\gamma^{T}) \tag{III.12}$$

When solved the yield function is:

$$G=e^{\alpha-\beta\gamma^{T}}-k \tag{III.13}$$

which represents a translation of the origin down the Y axis, and gives rise to the question of defining k. Intuitively, k should be some function of stocking and site quality. Garcia (1984) confronted a similar problem when defining closure of young stands, and represented it as a function of basal area and stems per hectare.

During the initial growth phase, when the RGM has little influence on the shape of the function, basal area functions approximate exponential functions, and k can be usefully defined as follows:

$$G_T=\alpha N_0 T^{\beta}-k \tag{III.14}$$

where N_0=initial stocking. If G=0:

$$k=\alpha N_0 T_{G=0}^{\beta} \tag{III.15}$$

where $T_{G=0}$ is the time at which G=0, and therefore:

$$G_T=\alpha N_0 T^{\beta}-\alpha N_0 T_{G=0}^{\beta} \tag{III.16}$$

$T_{G=0}$ can be obtained from the height function, resulting in compatible height and basal area functions, where G=0 when height = 1.40 m. Such an approach results in a certain lack of independence, but no bias should result from it, and it would therefore be similar in effect to the use of multiple measurements from permanent sample plots, i.e.: the magnitude of the residual mean square would be artificially reduced. This might be avoided by simultaneously estimating the parameters of the height and basal area functions, however, any height measurements less than 1.40 m have no associated dbhob measurements.

It is anticipated that the parameters might be linearly related to measures of site quality, dummy variables denoting site preparation and their interactions. This represented a change from the conceptual structure shown Figure II.2 to that shown in Figure III.1, where the state of the stand at age 5 is a function of site characteristics prior to modification, site modification strategy, and state of seedlings after planting. This change in structure was necessary because variables relating to site state before and after manipulation had not been measured in the experiments from which growth and mortality data were available.

Parameters for the initial growth model were all estimated with the functions in yield form, for two reasons:

(i) dbhob was measured only once in many of the available site preparation experiments;

(ii) when deciding on site preparation treatments, managers would be unlikely to know of tree dimensions other than at planting, and a projection from other ages was unnecessary.

Models in difference form may eventually be useful for representing the development of young crops with varying levels of weed competition from year to year. There were inadequate data available, however, to build such models during the studies described here.

Given these models, managers will require means of evaluating the relative worth of alternative establishment strategies, a task which includes rotation-length growth and yield prediction. Theoretical aspects of rotation-length extrapolations of treatment effects measured or predicted during the establishment phase are considered in the next section.

III.4 LONG-TERM EXTRAPOLATIONS OF INITIAL TREATMENT EFFECTS

Initial growth models for plantations in North America included analyses of the cost-effectiveness of site preparation which evaluated only the short-term effects of treatments (Payandeh 1987, Belli 1987). These were clearly inadequate, as shown by Belli (1987), who found that rankings of establishment strategies varied depending on whether the index of performance was cost/surviving tree or cost/1000 cm of summed tree height growth.

Although improved tree survival, better stem form, and more uniformity in tree size may confer immediate financial benefits through reductions in selection ratios, a complete evaluation of the worth of treatments applied during the establishment phase should include an evaluation of any resulting increases in growth rate throughout the life of a crop, and how such improvements might impact on the worth of an entire forest estate.

Snowdon & Waring (1984) identified two alternative responses of plantations to site preparation treatments. Response type I represented an initial gain in productivity which was not sustained throughout the rotation, while response type II was a sustained growth increase. A type I response might result from a treatment such as weed control, which temporarily increased growth inputs to a stand, and would be characterised by parallel yield trajectories, where the initial gain in time was constant after the growth improving factor ceased to affect growth.

It is here suggested that at least five assumptions would be necessary in order for a treatment to produce a type I response:

(i) the growth input change should be temporary, with site quality in the treated and untreated blocks returning to equivalent potential after a time;

(ii) the site should be capable of supporting more rapid growth, that is, the growth input increase should not result in some other deficiency at some point during the crop rotation;

(iii) future treatments, such as thinning, should not bring about a resumption of the treatment effect;

(iv) there should be no significant change in allometric relationships caused by the treatment, such as ratios between root and leaf surface areas;

(v) there should be no significant physiological age differences between the treated and untreated stands at respective times of equivalent yields.

Attempts to use traditional growth and yield modelling systems to extrapolate from experiments designed to investigate the effects of treatments during the establishment phase, such as that by Glass (1985) should include a consideration of the above assumptions.

Assumptions (iv) and (v) may be especially likely to be violated. Root to shoot ratios, for example, have been shown to change in response to improvements in fertility (Nambiar 1980), and changes in plant form, allocation of carbon, and development of heartwood with physiological age were reviewed in Chapter II.

Nevertheless, apparent type I responses have been reported after weed control (Preest 1977), soil cultivation (Wilhite & Jones 1981, Mason *et al.* 1989), and fertilisation (Woollons *et al.* 1988). Snowdon & Waring (1984) reported type 1 responses after weed control, and type II responses after fertilisation.

Determining the exact nature of a stand's response to an establishment treatment currently requires long-term monitoring of growth, especially if the response is of type II, but this may not always be the only alternative means of evaluation. Higher resolution stand models containing models of sub-processes, such as those envisaged by Jarvis (1981), may allow long-term predictions of effects of a wide variety of treatments, including site preparation, nursery & tree handling practices, and genetic improvement. Snowdon & Waring (1984) suggested that growth models of high resolution with respect to physical and chemical processes such as the fate of fertilisers after application, and with respect to biological processes such as responses to enhanced nutrition may ultimately provide a reasonably accurate means of assessing long-term effects of fertilisation.

Mathematical representations of initial survival and growth can be seen to rely heavily on exponential functions. This is expected, given a lack of between-tree competition, and the influence of allometric relationships between modelled variables and sizes of those plant parts directly associated with growth. For dbhob and basal area, an adjustment was required to preserve these allometric relationships, as dbhob=0 when trees already have considerable capacity to grow. Rotation-length considerations of the effects of establishment-related treatments require either fairly dubious assumptions, the development of more refined rotation-length models, or many rotation-length experiments. It was not intended that adequate long-term models of site preparation effects would result from the studies reported here. It was intended, however to take the first step towards an effective establishment decision-support system by accurately modelling survival, growth, and the effects of treatments prior to the onset of crown closure on a range of sites. A prerequisite to this modelling was the identification of the extent to which trees compete during the first few years after establishment, and data from Nelder experiments were employed for this purpose, as set out in the next chapter.

CHAPTER IV

NELDER EXPERIMENTS

Data from Nelder design experiments were used to explore the degree to which competition occurs during the initial growth phase, and to explore the difficulties experienced in building basal area/ha models which describe both the initial growth phase and growth at older ages.

VI.1. METHODS

1) Data available

a) Nationwide. A catalogue was compiled of Nelder spacing experiments which might be used to build growth models. Criteria for selection were:

(i) the species grown should be *Pinus radiata* D.Don;

(ii) measurements of height, dbhob and/or root collar diameter should be available between ages 0 and 5;

(iii) the seedlings should have been established through a bare-root system, with handling and planting methods to as high a standard as possible.

Fifteen Nelder spacing experiments satisfying these criteria were available. A summary of the locations and designs of the experiments is shown in table IV.1.

Table IV.1 - Nelder design initial spacing experiments for radiata pine

Name	Number of circles	Stocking range (N/ha)	Year planted	Years height measured	Years dbhob measured
AK965	20	588-4453	1986	87	
Dillion N545/2	20	608-4453	1984	84,85,86	85,86,89
K/roa E	23	364-18032	1966	74	73-78,81
Eyrewell	20	608-4165	1986	87-89	
NN523	20	569-4022	1986	87,88	
K/roa N	23	462-26088	1966	70,71,73	70,71, 73-78, 81,83, 85,87
Rai Vlly N545/1	20	608-4453	1984	84,85,86	85,86,89
R2046/1	10	384-2655	1984	87,89	87,89
R2046/2	10	371-2700	1984	89	89
R2047	20	569-3303	1986	89	89
Silver Peaks	20	490-4165	1986	88,89	
K/roa S	23	455-24554	1966	70,71	70-78, 81,83, 85,87
Tasman	20	588-4453	1984	85,86,89	86,89
K/roa W	23	319-23019	1966		73-78,81
Wn366	20	588-4453	1986	87,89	

The Nelder experimental design was first proposed by Nelder (1962) to identify optimal spacings between plants in vegetable crops. Each experiment consists of a set of planting positions arranged at the intersections between equally spaced rays and concentric circles (Figure IV.1). Trees planted at these points in different circles are effectively growing at different spacings, with stocking increasing towards the centre of the plot.

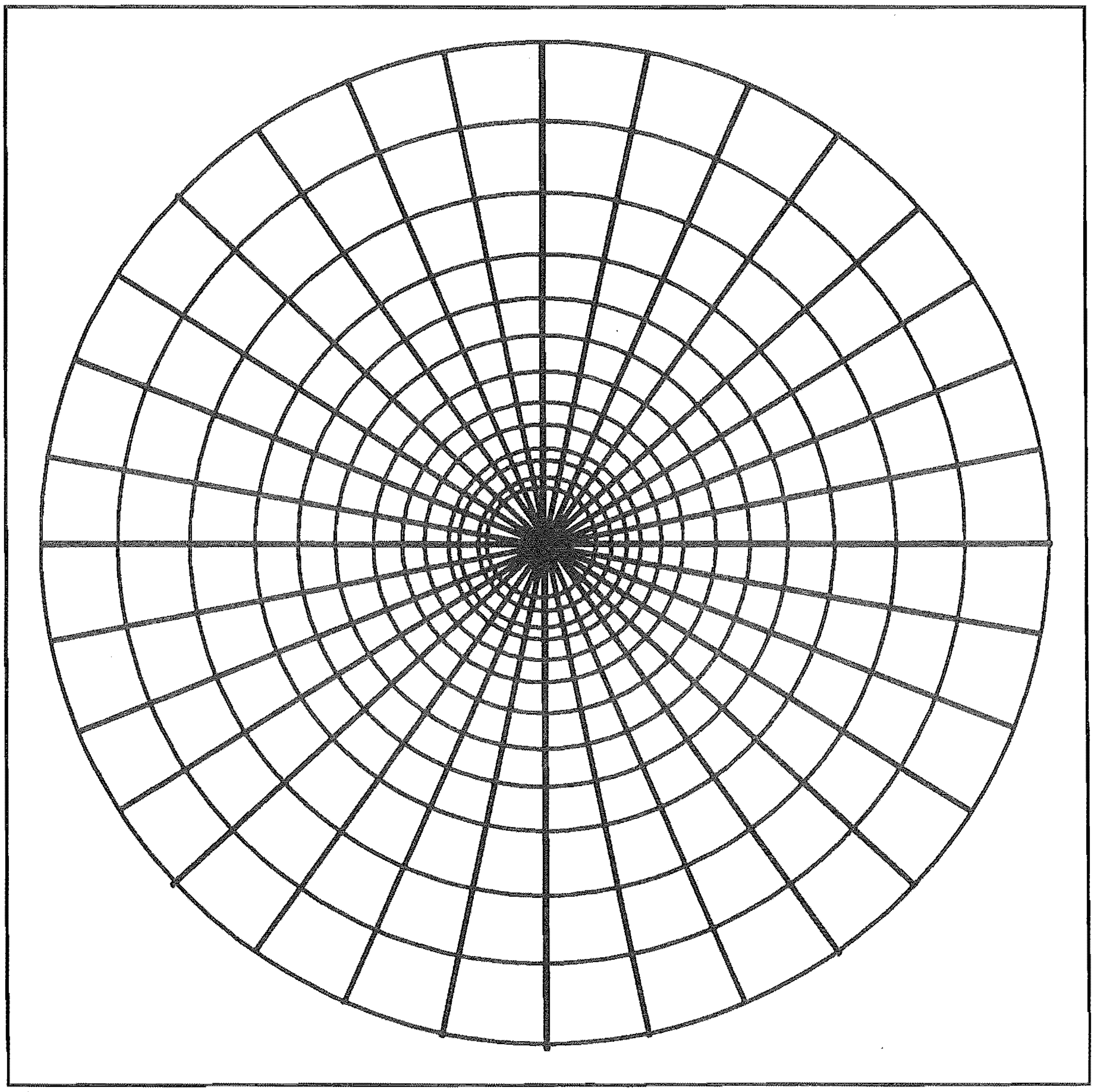

Figure IV.1 - Plan of a Nelder design spacing experiment. Trees are planted on the intersections of lines and circles.

Mean dbhob, mean height, basal area, and initial stocking were calculated for each circle of each Nelder for those years when dbhob had been measured.

2) Modelling methodology

Modelling was conducted with the SAS statistical software package (SAS Institute Inc., 1985) on a Digital VAX computer system. The main analytical procedures used were GLM for linear regression models, NLIN for non-linear models, UNIVARIATE for analysis of residuals, and PLOT for graphical portrayals.

The repeated measurements within plots lacked statistical independence so their analyses, in conventional form, would result in under-estimations of residual mean squares. Emphasis was placed, therefore, on the elimination of bias in fitting models, and on attaining as close to a normal distribution of residuals as possible using procedure UNIVARIATE. This last procedure includes reports of residual skewness, kurtosis, and a Kolmogorov-Smirnoff plot, indicating the departure from normality. In addition, the mean of the residuals was reported, which would be expected to be close to 0 if the model were unbiased. A residual mean of 0 can be achieved, of course, even when the model is biased with respect to an independent variable, but plots of residuals against independent variables were used to check for this eventuality.

3) Studies conducted

a) Competition. Mean dbhob and mean height were plotted against stocking for each circle and year of each Nelder experiment. These were then examined to determine whether or not dbhob or height varied with stocking at each age.

Data from six Nelder experiments; North, Rai Valley, R2046/1, South, Tasman, and Dillion were used to explore relationships between dbhob, height, and spacing prior to age 6. Multiple regression analysis with GLM was performed, individual tree dbhob being the dependent variable along with the following independent variables (plus their interactions):

(i) individual tree height;

(ii) initial stocking;

(iii) 1/initial stocking;

(iv) location (as a class variable);

(v) a dummy variable which was 1 if the age was greater than 4, and 0 otherwise.[1]

(vi) tree age at time of measurement.

b) Growth and yield modelling. Data from the North and South Nelders were used to model gross basal area/ha, G_i, vs time, T_i, with procedure NLIN. Several functions were

[1]. This variable was expected to enable the model to be sensitive to between-tree competition, which graphs of dbhob vs spacing suggested might be occurring after age 4.

tried in difference form:

(i) Schumacher forms:

$$G_2=\exp(\log(G_1)(\frac{T_1}{T_2})+\alpha(1-(\frac{T_1}{T_2}))) \tag{IV.1}$$

$$G_2=\exp(\log(G_1)(\frac{T_1}{T_2})^{\beta}+\alpha(1-(\frac{T_1}{T_2})^{\beta})) \tag{IV.2}$$

$$G_2=\exp(\log(G_1)(\frac{T_1}{T_2})^{\beta+\gamma N_0}+\alpha(1-(\frac{T_1}{T_2})^{\beta+\gamma N_0})) \tag{IV.3}$$

(ii) Gompertz:

$$G_2=\exp(\log(G_1)e^{-\beta(T_2-T_1)}+\alpha(1-e^{\beta(T_2-T_1)})) \tag{IV.4}$$

(iii) Hossfeld:

$$G_2=\frac{1}{\frac{1}{G_1}(\frac{T_1}{T_2})^{\beta}+\alpha(1-(\frac{T_1}{T_2})^{\beta})} \tag{IV.5}$$

In addition, the North Nelder data were used to model G_i in yield form, by stand density using a modified Gompertz function:

$$G_T=\exp(\alpha-\beta\gamma^{T}) \tag{IV.6}$$

In an attempt to improve the fit of the models for young stands, as explained in the previous chapter, the following modified Schumacher equation was fitted to data from each circle (stand density):

$$G_T = \exp(\alpha - \frac{\beta}{T}) - k \tag{IV.7}$$

The k parameter was multiplied by initial stocking during fitting, as this allowed NLIN to fit all circles with the same starting points.

A similar adjustment was made to function IV.6, by subtracting k, but the non-linear procedure could not be made to converge. This function was further modified to:

$$G_T = \exp(\alpha - \beta\gamma^{T}) - \exp(\alpha - \beta\gamma^{T_{G=0}}) \tag{IV.8}$$

where $T_{G=0}$ was the time at which mean height=1.40 m, estimated from the height growth model described in section V.3.b. Similar adjustments were made to the Hossfeld and Schumacher functions, and an attempt was made to fit them to the North Nelder gross basal area data.

IV.2. RESULTS

1) Competition during the initial growth period

a) Dbhob vs spacing. Plots of mean dbhob against initial spacing showed clearly that there was a relationship between mean dbhob and spacing at age 5 (Figures IV.2-IV.6) in all experiments where data were available, with the exception of the R2046 series, where the relationship was not clear (Figures IV.7 and IV.8).

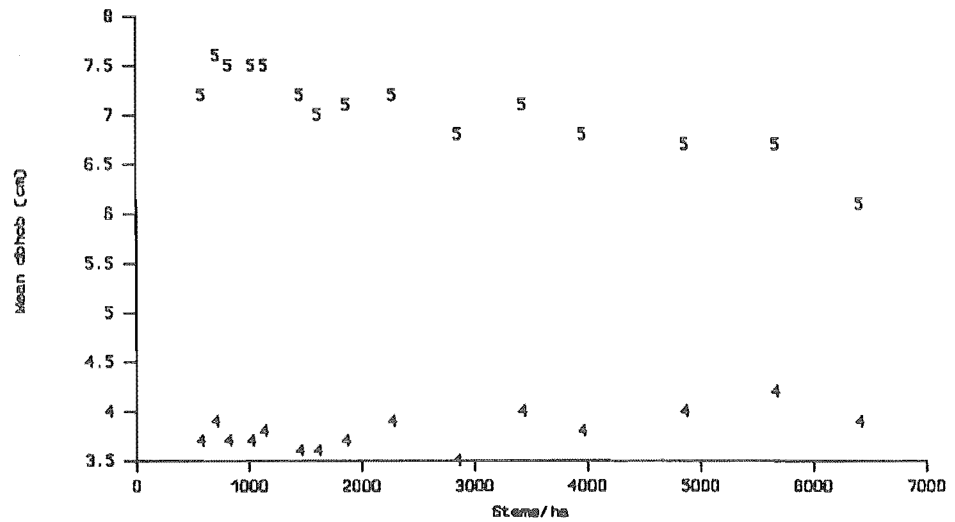

Figure IV.2 - Mean dbhob vs stocking in the Kaingaroa South Nelder-design experiment. Numbers denote the year of measurement.

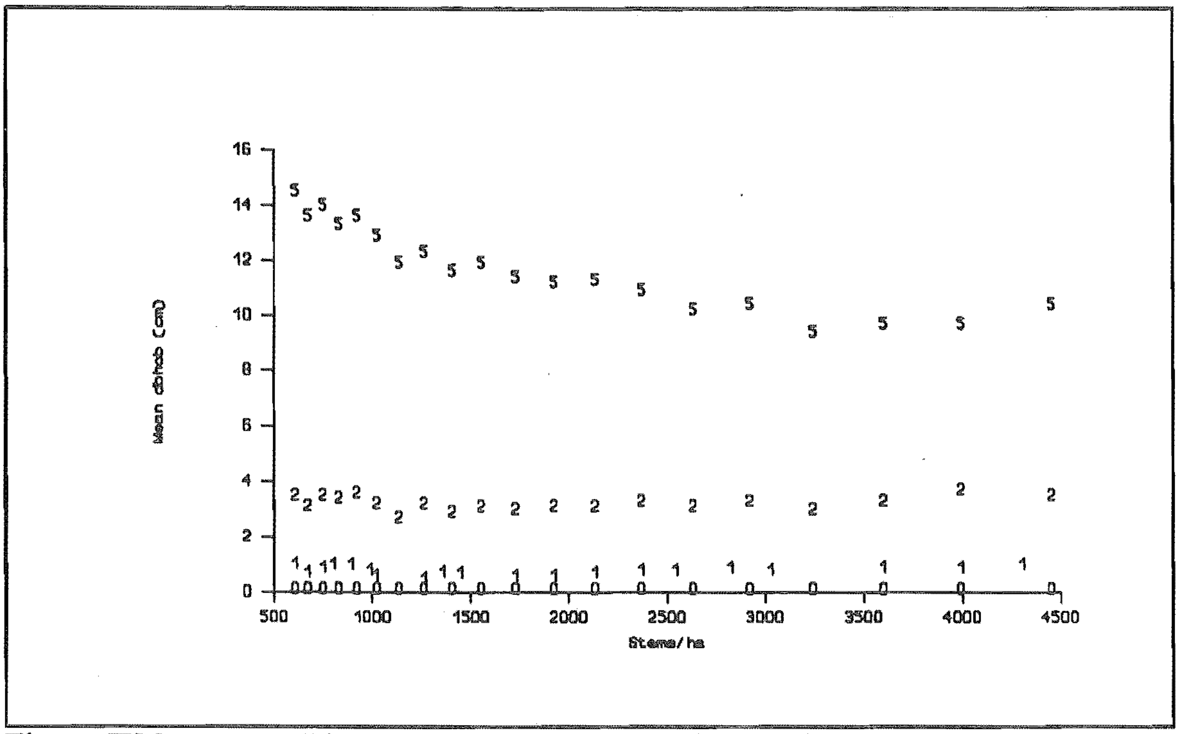

Figure IV.3 - Mean dbhob vs stocking at the Dillion Nelder-design experiment. The numbers denote the year of measurement.

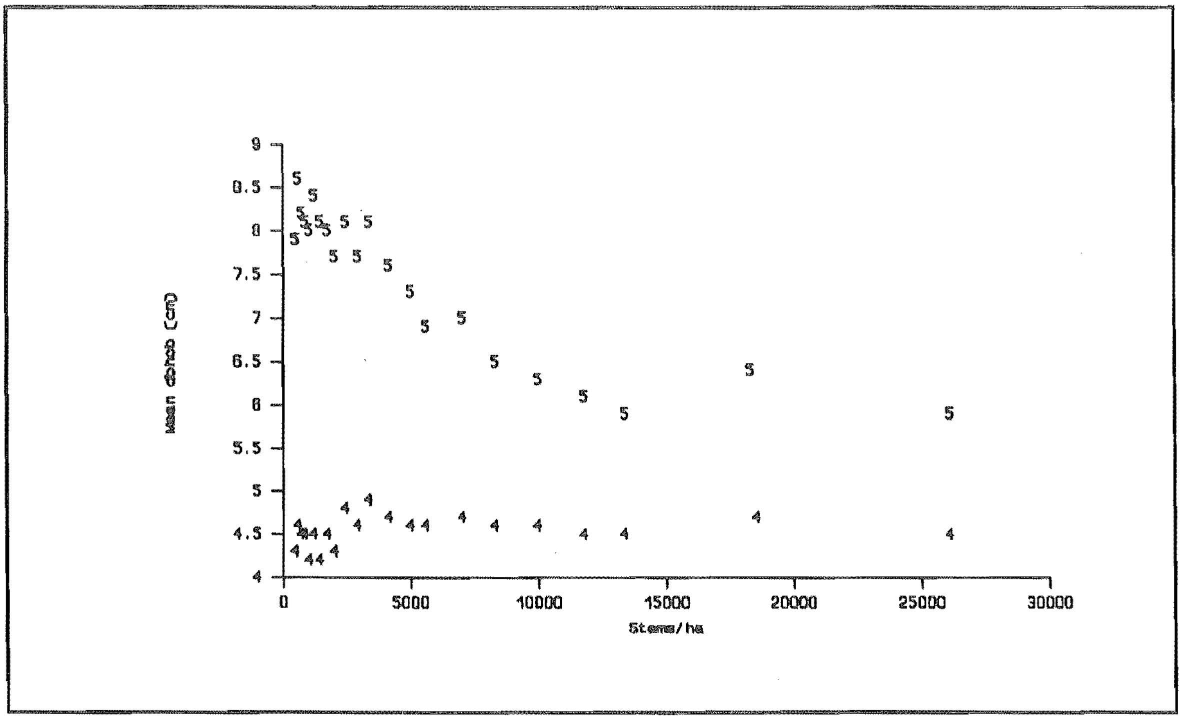

Figure IV.4 - Mean dbhob vs stocking at the Kaingaroa North Nelder-design experiment. Numbers denote the year of measurement.

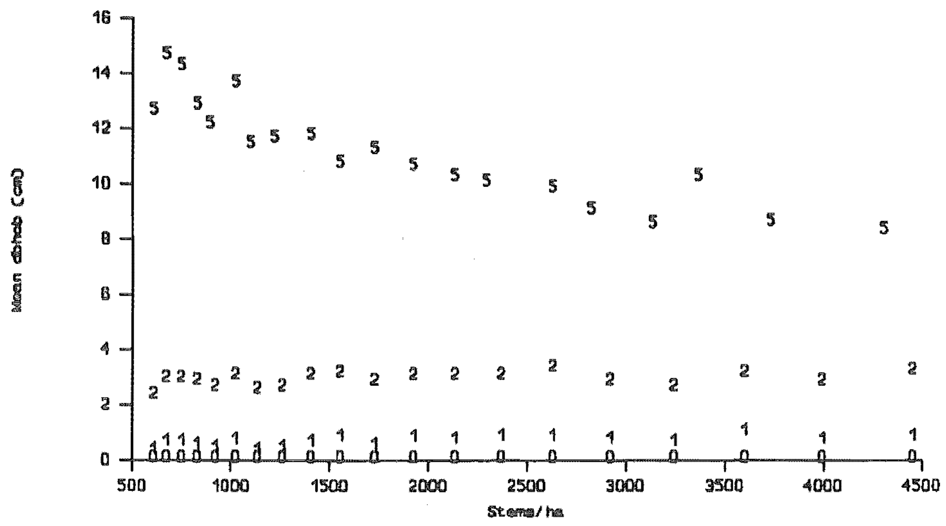

Figure IV.5 - Mean dbhob vs stocking at the Rai Valley Nelder-design experiment. Numbers denote the year of measurement.

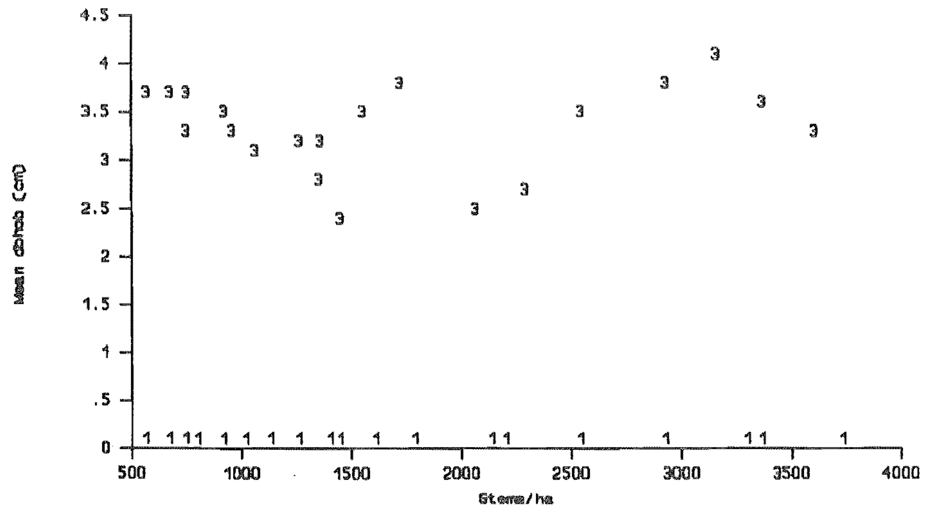

Figure IV.6 - Mean dbhob vs stocking in Nelder-design experiment R2047. The numbers denote year of measurement.

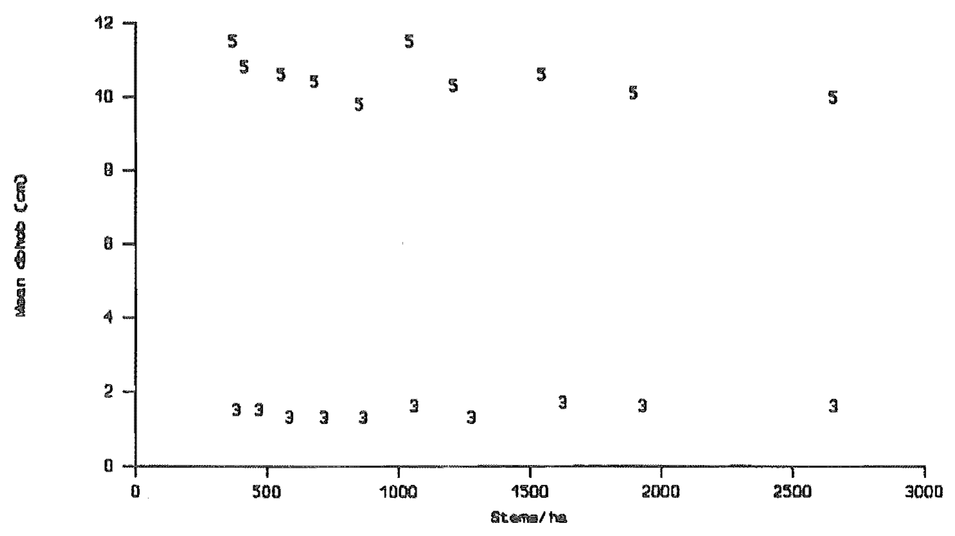

Figure IV.7 - Mean dbhob vs stocking in Nelder-design experiment R2046/1. Numbers denote year of measurement.

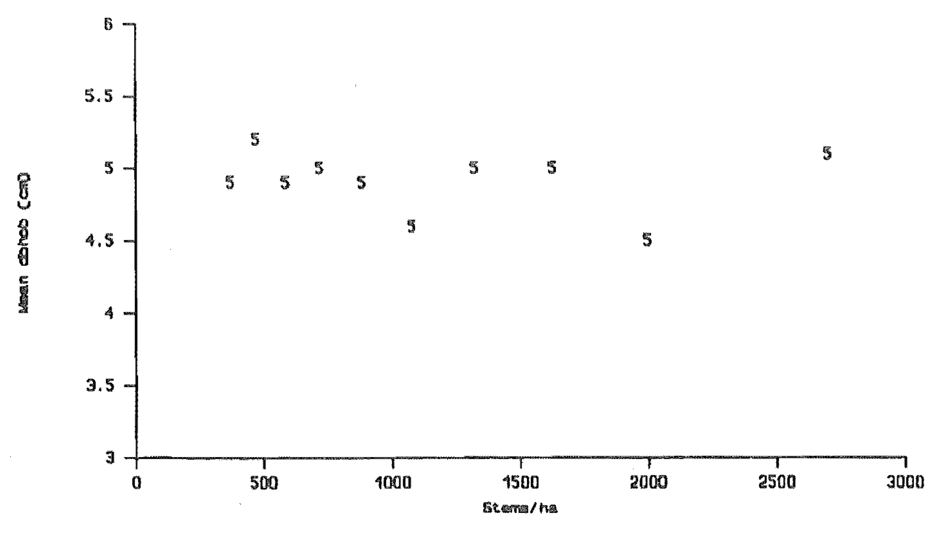

Figure IV.8 - Mean dbhob vs stocking at Nelder-design experiment R2046/2. Numbers denote year of measurement.

Prior to age 5, no correlation between mean dbhob and spacing was apparent in any of the experiments.

b) <u>Height vs spacing</u>. In the North and South Nelders, a correlation was found between mean height and initial stocking at ages 4 and 5, with height increasing as stocking increased between 400 and 5000 stems/ha in the South Nelder (Figure IV.9) and, to a lesser extent between 400 and 3000 stems/ha in the North Nelder (Figure IV.10).

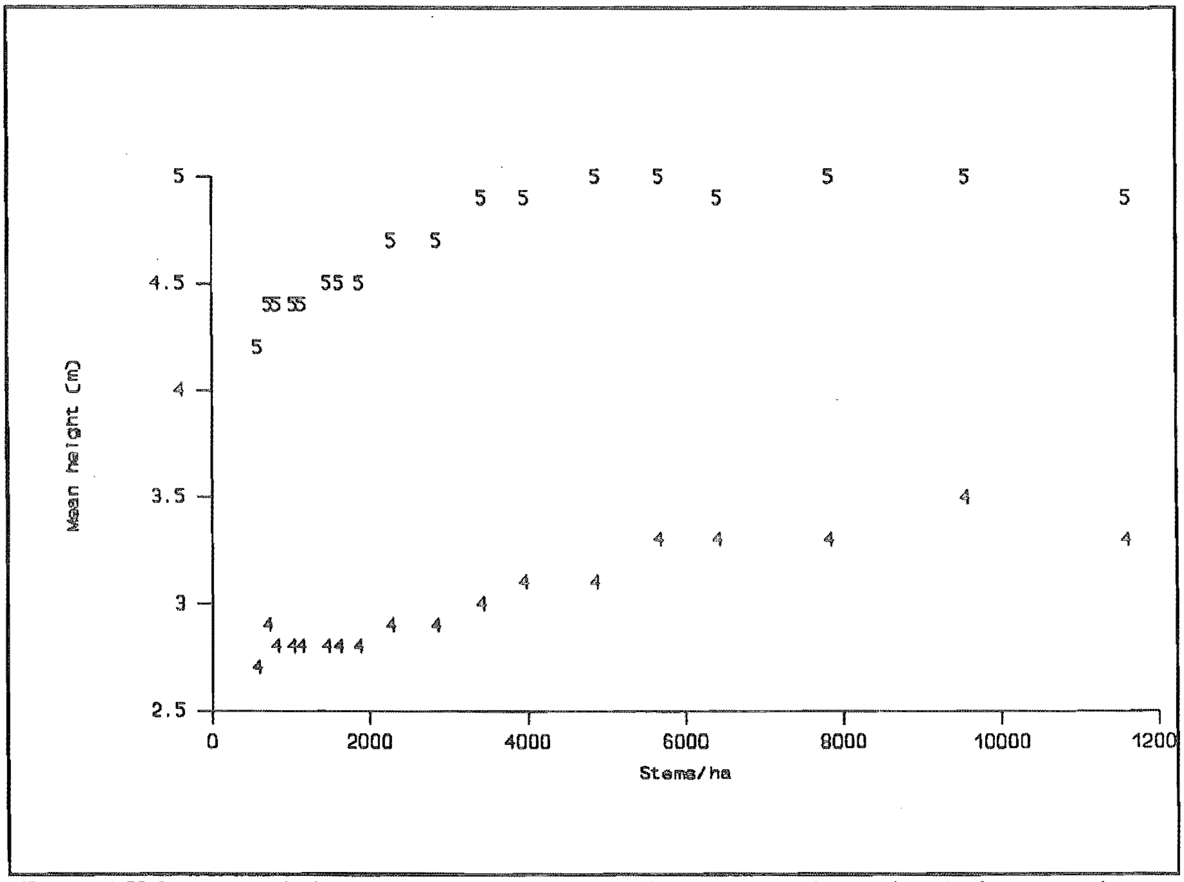

Figure IV.9 - Mean height vs stocking in the Kaingaroa South Nelder-design experiment. Numbers denote the age of measurement.

In three other Nelder experiments, correlations between mean height and stocking were less pronounced, but still evident. There was a suggestion of a similar relationship at age 5 at Te Teko (Figure IV.11), ages 1 and 2 at Rai Valley (Figure IV.12), and age 2 at Dillion

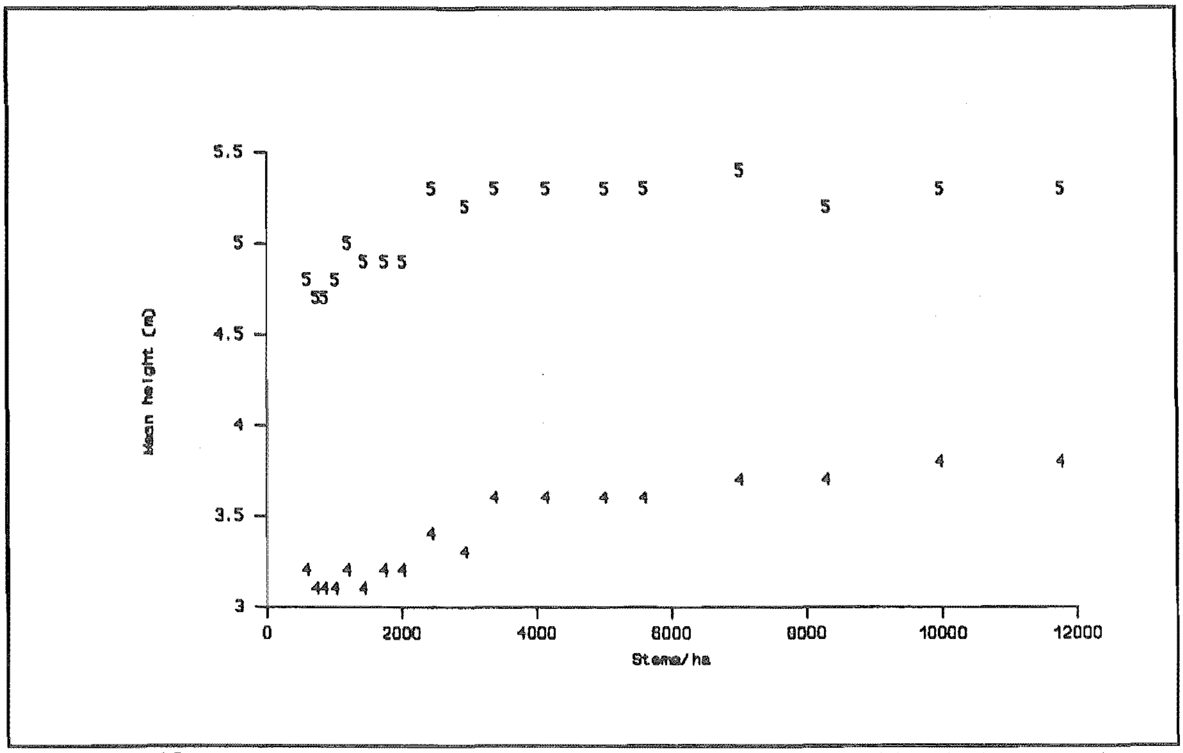

Figure IV.10 - Mean height vs stocking in the Kaingaroa North Nelder-design experiment. Numbers denote the age of measurement.

(Figure IV.13).

Heights and stockings from R2046/1, R2046/2 and R2047 showed no clear correlations.

c) <u>The relationship between dbhob and height</u>. Mean dbhob of trees within circles was found to increase with height, decrease with initial stocking after age 4, and increase with height * 1/(initial stocking). Tree age was not a significant predictor.

Interactions between location (a class variable) and the three other independent variables were all significant. Residuals were normally distributed, 95% were within ±3 cm of the predictions, and they were unbiased.

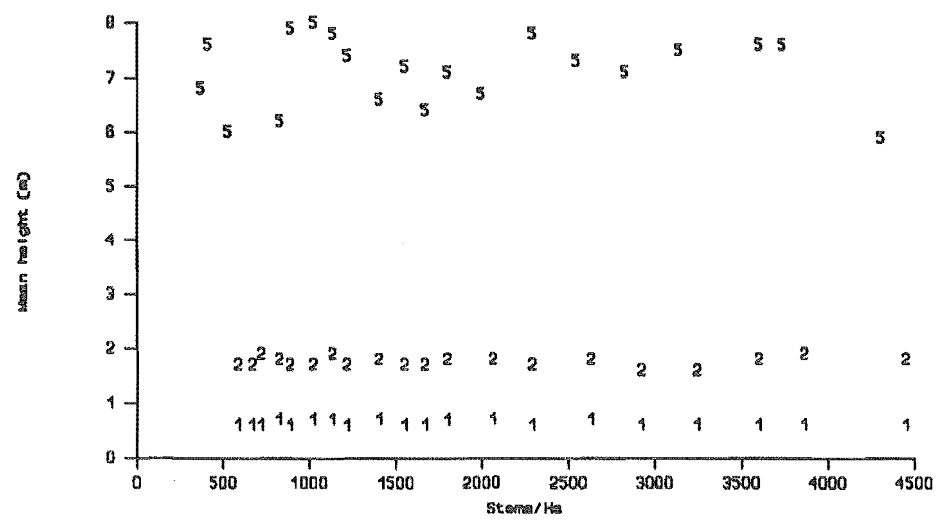

Figure IV.11 - Mean height vs stocking in the Tasman Nelder-design experiment. Numbers denote the year of measurement.

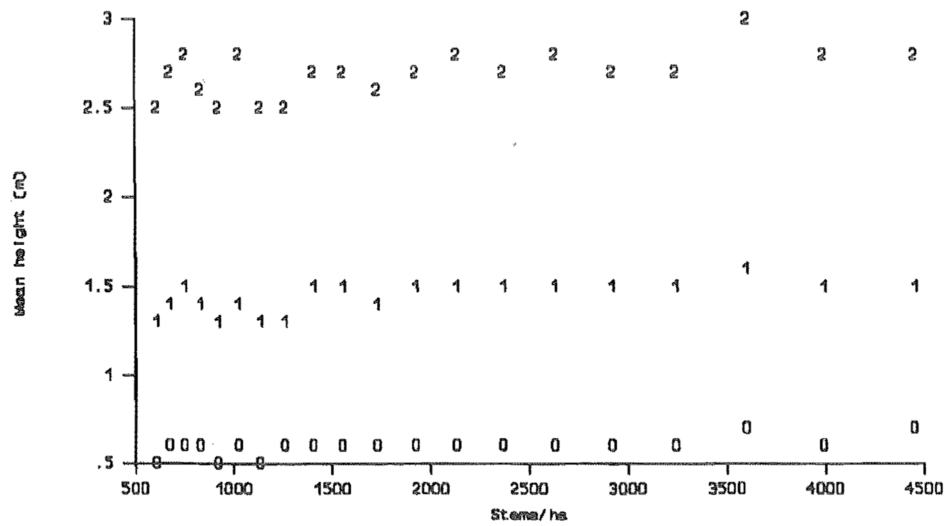

Figure IV.12 - Mean height vs stocking in the Rai Valley Nelder-design experiment. Numbers denote the year of measurement.

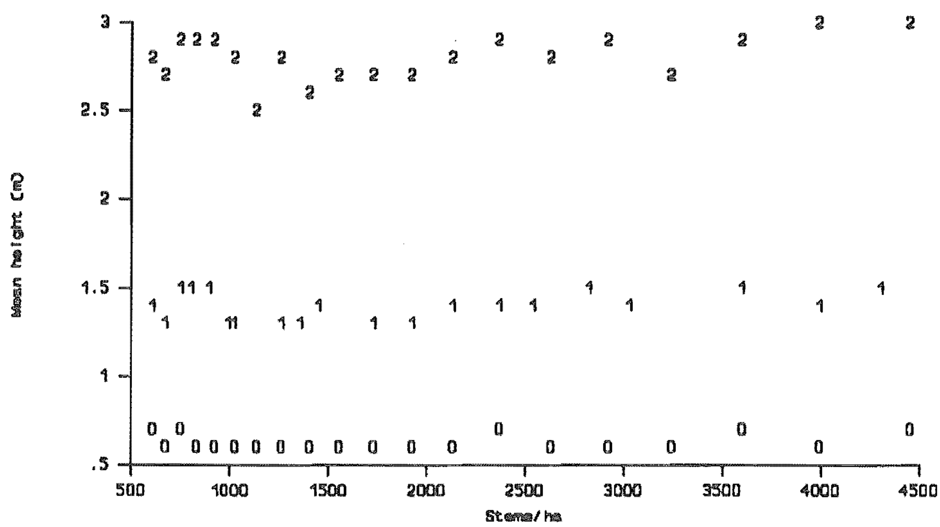

Figure IV.13 - Mean height vs stocking in the Dillion Nelder-design experiment. Numbers denote year of measurement.

2) Modelling basal area in the North Nelder (K/roa N)

Models fitted with functions IV.1-IV.5 had residual distributions which exhibited extreme bias with respect to predicted gross basal area/ha (G) and time (T). Figures IV.14 and IV.15 show typical residual distributions. Although there was evidence of poor fit at most ages, the bias was particularly apparent for small values of T.

When data with T<6 were excluded, models were found to be less biased with respect to time (for example function IV.5 (Figure IV.16)), but there was still evidence of bias with respect to predicted G.

Fitting function IV.6 to each circle individually, in yield form, resulted in a similar

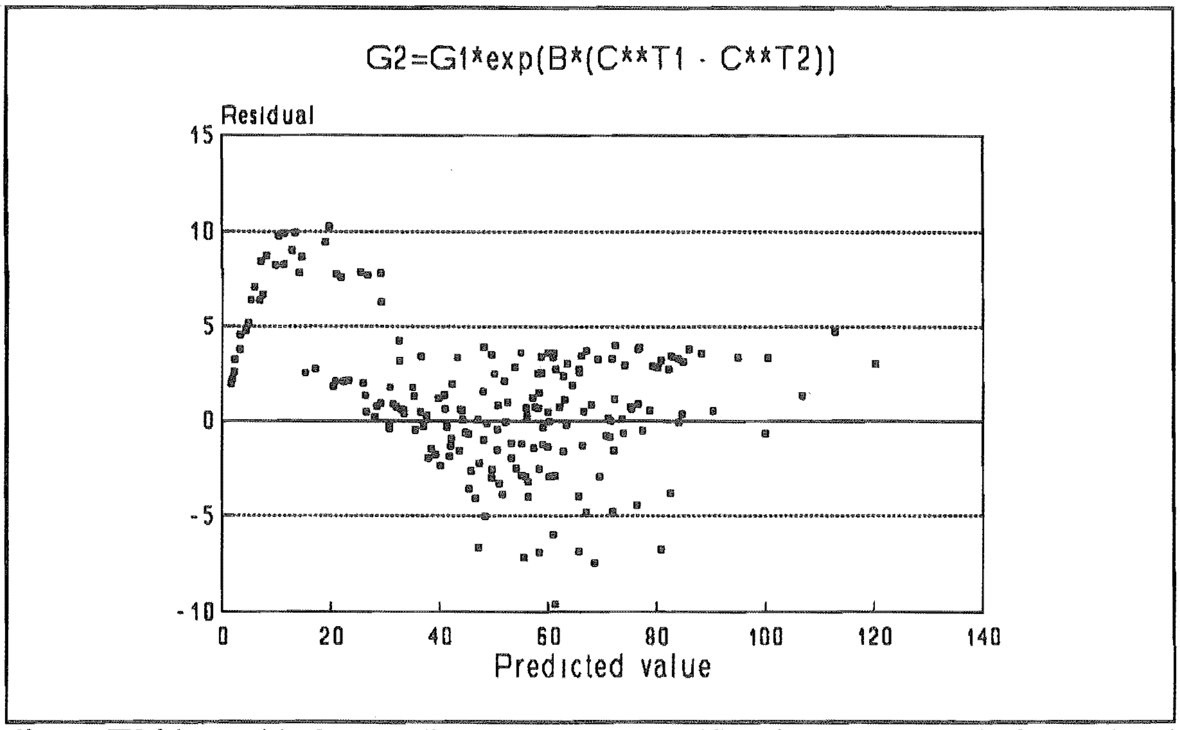

Figure IV.14 - Residual vs predicted values for modified Gompertz model of gross basal area/ha in the North Nelder plot

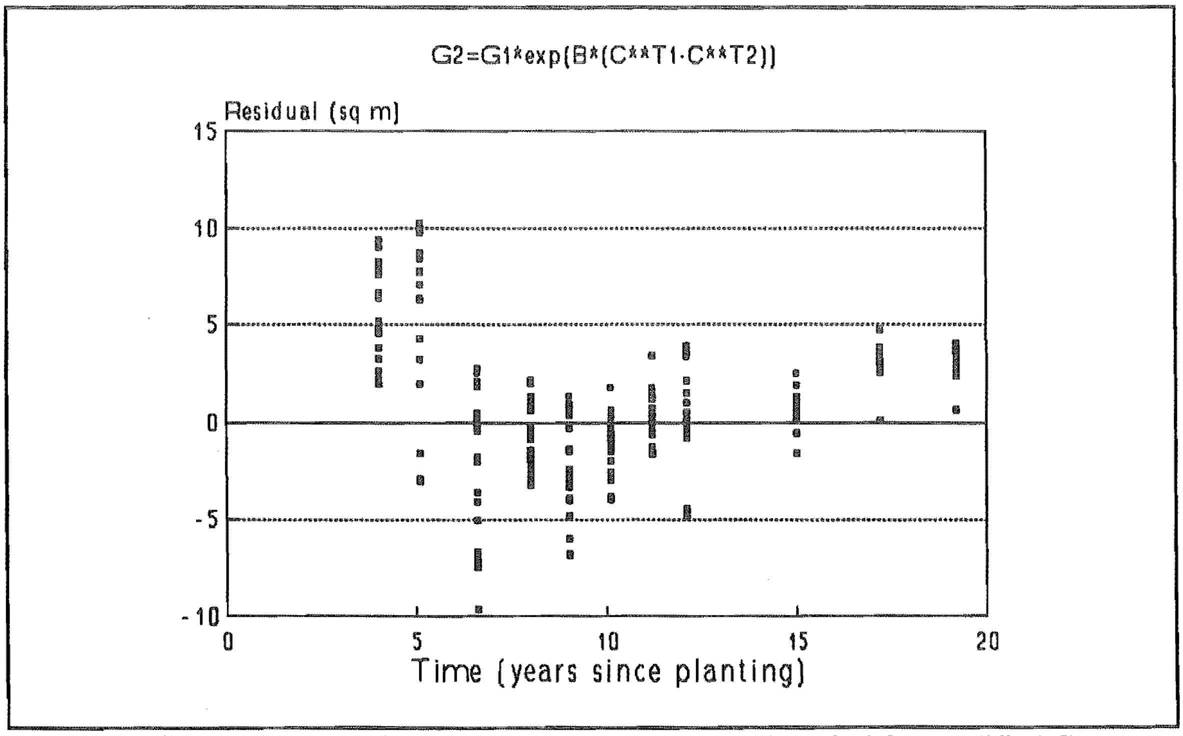

Figure IV.15 - Residual vs time at the beginning of growth period for modified Gompertz model of Kaingaroa North Nelder-design basal area/ha data.

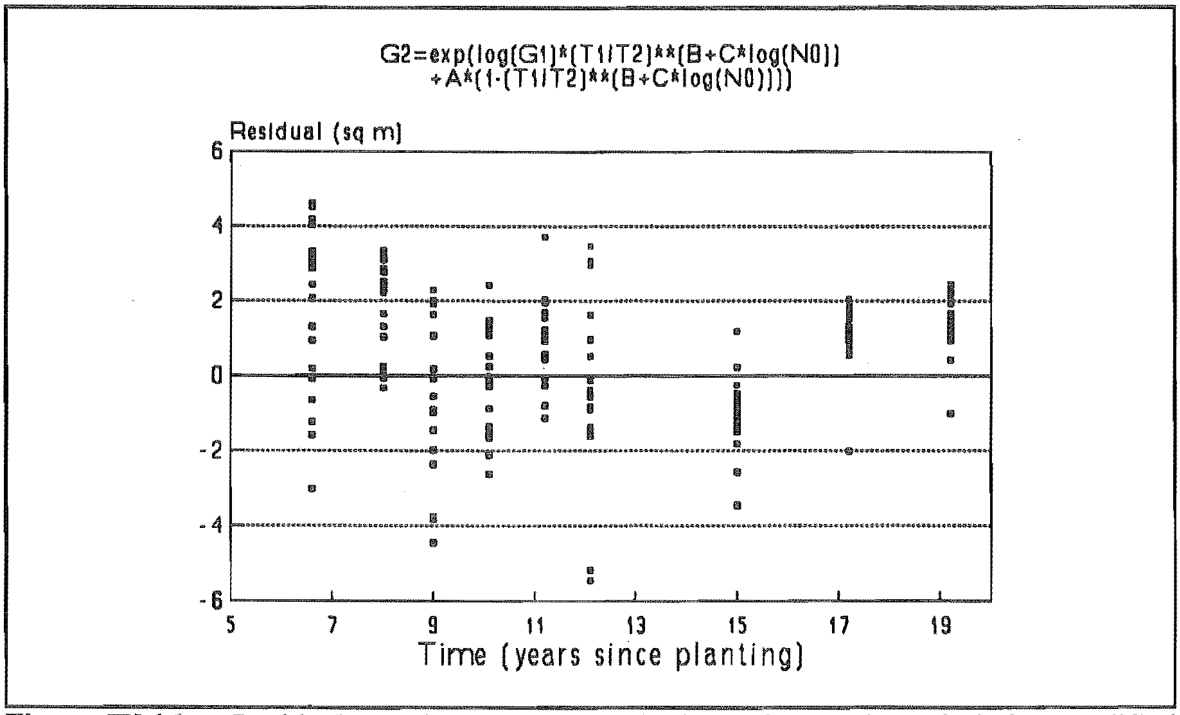

Figure IV.16 - Residual vs time at the beginning of growth period for modified Schumacher model of Kaingaroa North Nelder-design experiment basal area/ha data, excluding data less than 6 years old.

bias with respect to time (Figure IV.17). Plots of fitted curves for the highest and lowest stockings/ha showed that models under-estimated growth for the youngest ages (Figure IV.18).

Adding a modifier (k in function IV.7), as discussed in chapter III, resulted in an improvement in the residual distributions (Figure IV.19). The models were easier to converge when k=f(initial stocking/ha), but a relationship between k and initial stocking/ha could not be clearly demonstrated. Functions with three parameters proved difficult to converge when k was added as an extra parameter, and may have produced ill-conditioned matrices.

Plots of mean annual gross basal area increment between measurements against time showed some unexpected small peaks at older ages. The main peak in basal area/ha occurred earlier the higher the initial stocking (Figure IV.20).

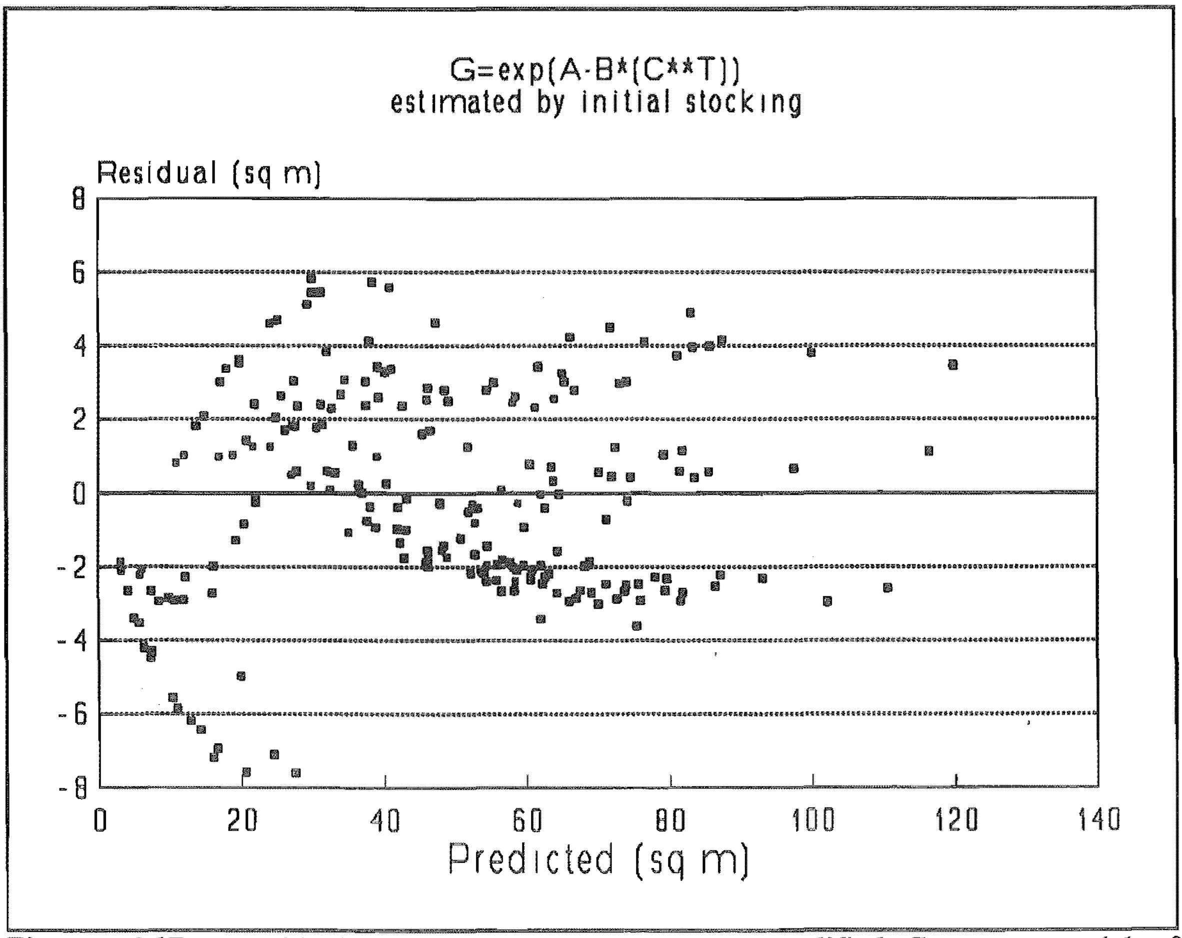

Figure IV.17 - Residual vs predicted values from a modified Gompertz model of Kaingaroa North Nelder-design experiment data. The model was fitted to each circle individually, in yield form.

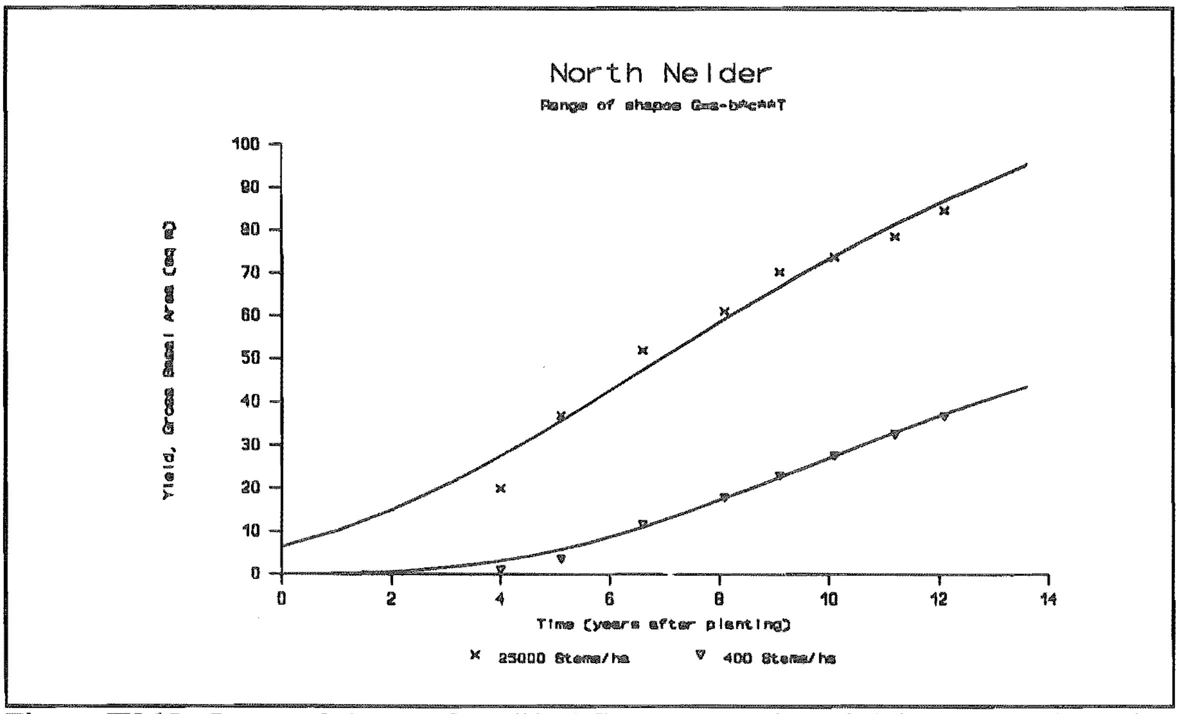

Figure IV.18 - Range of shapes of modified Gompertz models of Kaingaroa north Nelder-design experiment data. The models were fitted to each circle individually in yield form. Raw data are also plotted - note the poor estimate of growth at ages 4 and 5.

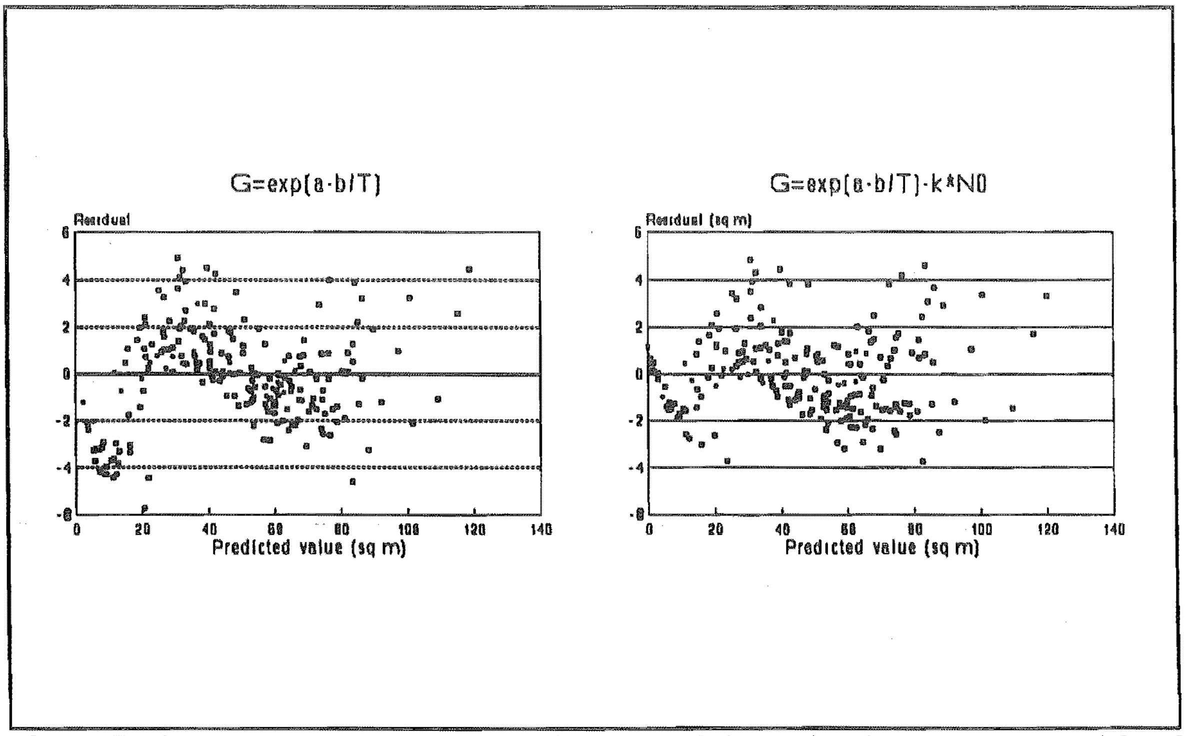

Figure IV.19 - Residual vs predicted values from Schumacher basal area/ha models of Kaingaroa North Nelder-design experiment data. Models were fitted in yield form to each circle. The right hand plot includes the k adjustment.

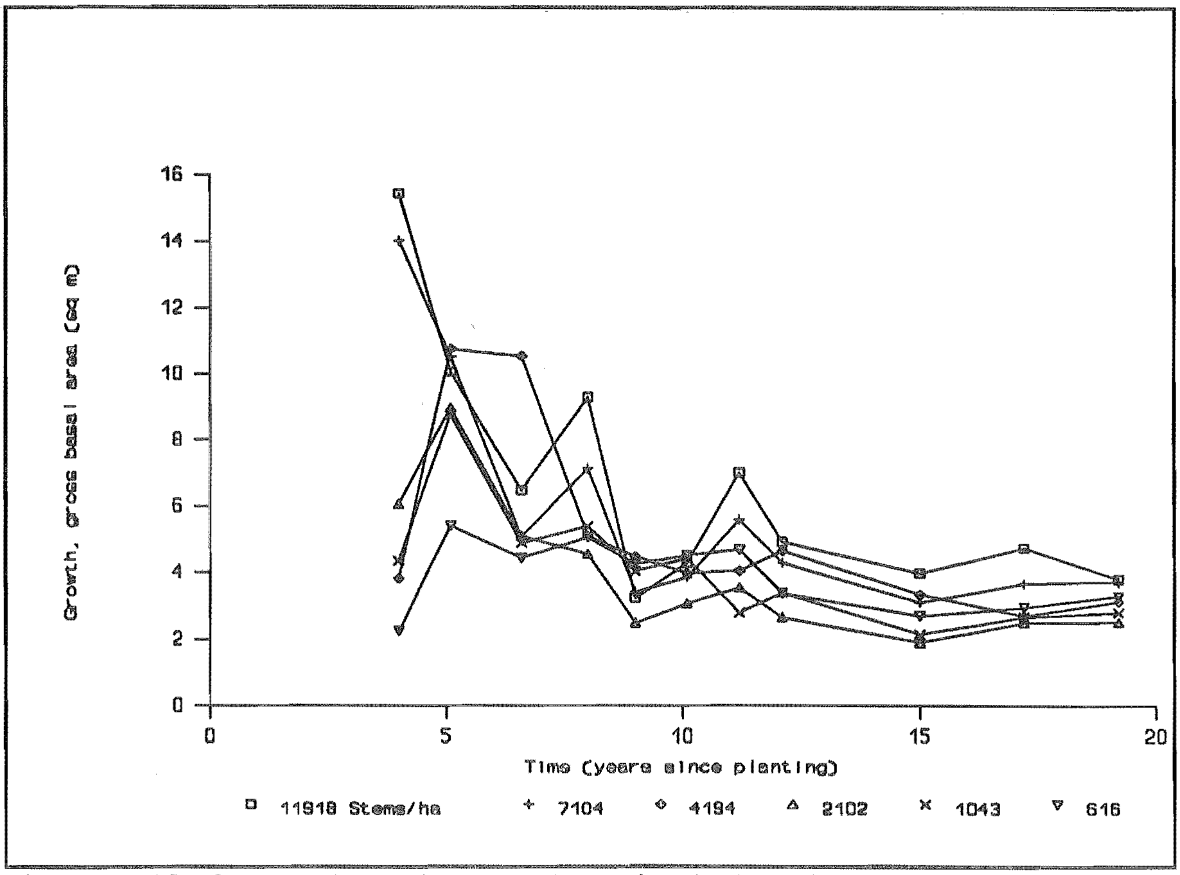

Figure IV.20 - Growth of gross basal area/ha vs time in the Kaingaroa North Nelder-design experiment.

IV.3. DISCUSSION OF THE ANALYSIS OF NELDER EXPERIMENTS

1) Competition during the initial growth period

As discussed in chapter III, identifying when young plantation trees begin to compete is an important prerequisite to modelling initial growth and mortality. Prior to competition, for instance, one might expect that mortality models should be anamorphic, while competition-related mortality is probably best represented by a polymorphic function. In addition, one might expect that stand yield functions would be exponential for young stands prior to competition. Garcia (1990) found closure to be very useful as a state variable in models of older radiata pine crops.

a) Dbhob vs spacing. Plots of dbhob vs stocking/ha in all the Nelders showed no relationship between these two variables prior to age 5. This might indicate that the trees were effectively free-grown prior to this age. Menzies *et al.* (1992) reported that, in two initial spacing experiments, with treatments ranging from 200 to 600 stems per hectare, there were no inverse correlations between dbhob and initial spacing up to age 5 in one case, and up to age 6 in the other.

West *et al.* (1982) found that basal area/ha growth was unaffected by pruning when residual crown lengths were above approximately 4.5 km/ha, which implied that radiata pine should be actively competing when the sum of crown length per hectare exceeds this value. Many of the circles in the Nelder experiments reported here were carrying far more than 4.5 km crown/ha long before any competition was observed. For example, at 4500 stems/ha, 1.5 metre tall trees would have had the equivalent of almost 6.8 km of crown per hectare, and the 12 000 stems/ha circles would have had far more. At age 4, when no relationship between diameter and initial stocking was evident in the North Nelder, the mean height in the inner circles was more than 3.5 metres. The two studies may have resulted in different conclusions because of differences in the ages and stockings of trees measured. The crown km/ha measurement takes no account of the correlation between width of non-cylindrical crowns and vertical position on individual trees. Young trees studied in the Nelder analysis would have had far less average leaf surface area/length of crown than would the older trees studied by West *et al.*, because their mean crown widths would have been much smaller.

b) Mean height vs spacing. Plots of mean height vs stocking/ha, showed height *increased* with stocking prior to age 5 in some of the Nelders. Results from two experiments designed with initial spacings as treatments in incomplete blocks showed the same trend (Menzies *et al.* 1992). The observed correlation between height and stocking/ha may have been due to very competitive weeds occupying a smaller proportion of the total ground surface in more highly stocked circles. Weeds were not controlled in the North and South Nelders where the correlation was strong, while they were controlled to some extent (by line slashing) in all the others, where the correlation was weaker (R.B. Tennent, pers. comm.). This explanation implies that the weeds were more competitive than the crop trees. Species have been found to differ in competitive ability (Richardson 1991), but the weed species present in the Nelders were not recorded, and although research is in progress, no measures of relative plant competitiveness are yet available for New Zealand conditions (B. Richardson pers. comm.). If the effect were due to weed competition, one might expect differences would be greater in diameter growth than in height growth (Lanner 1985, Richardson 1991), and this was clearly not the case.

Another explanation for the correlation between stocking/ha and height may be that more closely stocked trees provided mutual shelter. Exposure to wind has been shown to reduce the yield of plants, measured as dry weight, leaf area or height (Grace 1977).

It would be interesting to know whether the correlation between initial stocking and height was affected by the organisation of the stand (eg: group planting vs even spacing); whether it affected the incidence of toppling; and whether any worthwhile harvestable yield increases might accrue from higher initial stocking (for any given final crop stocking).

c) The relationship between diameter and height. Diameter was found to be a function of height; the dummy variable indicating age > 4; spacing; and location. This reflected results from the analysis of diameter vs spacing, in that diameter decreased with stocking only after age 4, or with decreasing height*(1/stocking). The latter variable allowed for a curvilinear relationship between height and stocking.

Interactions between location and the independent variables were significant in the multi-linear analysis, indicating that generating diameter distributions from height distributions in an initial growth model would not offer a way to overcome the problem of small numbers of dbhob measurements in the existing database. Any definition of the change in diameter vs height vs site and treatment factors would be no better than a directly estimated diameter distribution model.

The implications of these results for modelling initial survival and growth are:

(i) anamorphic mortality functions are more likely to fit the data than polymorphic ones, as no between tree competition was detected prior to age five;

(ii) exponential functions are likely to provide a good representation of initial height and basal area growth, as trees' capacities to grow would be limited by their existing sizes, and be unaffected by between-tree competition;

(iii) stocking/ha may be a useful independent variable in an initial height model.

2) Modelling basal area in the North Nelder

Modelling basal area/ha growth and yield in the North Nelder experiment enabled the development of some useful ideas relating to early growth, but the resulting models were not free from bias.

Clearly, adding a term (k) to allow for allometric assumptions in traditional growth functions resulted in a reduction in bias of models with respect to time, but none of the modified functions was completely free of bias. Plots of mean annual increment between measurements suggested that there were considerable variations in growing conditions from year to year, and much bias in model residuals may have resulted from this. One might have expected that k would be related to initial stocking/ha and site quality. It was not possible to test for the latter, and no conclusive proof was found for the former, although, in one run of procedure NLIN, multiplying k by initial stocking did facilitate the setting of initial values for the k parameter over a range of models estimated by initial stocking.

Garcia (1984) found that, for a model of radiata pine growth in Golden Downs Forest, estimated differential equations gave good fits within the range of available data, but were unreliable for heights less than 6 m. Using a similar rationale to the one described here, he assumed that, for initial growth, closure was a function of $\alpha G+\beta N$, where N was initial stocking. A lack of initial growth data meant that this assumption could not be tested, and the model chosen for Golden Downs contained a separate, assumed model of initial growth.

The initial growth model adopted calculated an average basal area at mean height 7 m as a function of stocking.

Maximum basal area/ha growth occurred earlier with higher stockings in the North Nelder, which reflects an earlier onset of canopy closure. It was therefore surprising to find no relationship between dbhob and stocking until age 5.

The implications of the results reported here for initial growth modelling were that:

(i) exponential models of initial basal area growth should contain a modification to allow them to conform to allometric assumptions;

(ii) the value of the term representing growth capacity at height equal to 1.40 m may be related to initial stocking;

(iii) initial stocking is one of the most important independent variables in fitting models of initial basal area growth.

These implications formed a basis from which to begin modelling initial survival and growth, using data from site preparation experiments, as set out in the next Chapter.

CHAPTER V

MODELLING INITIAL GROWTH

On the basis of results from the Nelder analysis, data from 27 site preparation trials were used to create a mathematical model of growth between 0 and 5 years of age that was sensitive to variations in site quality and management strategy. The specific objectives of this investigation were:

(i) to find ways of representing information from site preparation experiments to maximise its utility for decision-making;

(ii) to provide starting points which reflect differential site preparation for existing growth models that cover older crops.

V.1. METHODS

1) Data available

a) Nationwide. A catalogue was compiled of site preparation and other experiments, throughout New Zealand dealing with radiata pine establishment, which contained treatments that might be used to build growth models. Criteria for selection were:

(i) the species grown should be Pinus radiata D.Don;

(ii) measurements of height, dbhob and/or root collar diameter should be available between ages 0 and 5;

(iii) the stock planted should be grown from either climbing select seed (see glossary) or from seed orchard seed with GF ratings ranging from 6 to 13 (most data available were from experiments with seed of this quality, and it was considered that an evaluation of the effects of higher quality seed would require more data from stands with improved genotypes than were immediately available);

(iv) the seedlings should have been established through a bare-root system, with a certain minimum standard of handling and planting method.[2]

A catalogue of 131 experiments meeting these criteria was assembled. This catalogue did not include all suitable experiments; data from Kinleith Forest and from sites in the South Island were omitted because the nature and location of the experiments could not be determined in the time available. A summary of the location, measurement, and treatments for 122 of the 131 experiments has been reported previously (Mason 1991a).

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[2].In some cases, data were available on the same site from either several establishment techniques, or two levels of nursery, handling and planting quality. It was considered that an analysis of the effects of other establishment techniques or of poor nursery, handling and planting practices on a range of sites would require more data than were immediately available.

Data were available from 60 of the 131 experiments. These were summarised by location, ripping, mounding, phosphate fertilisation (15 gm/tree after planting, or the closest equivalent), nitrogen fertilisation (15 gm/tree after planting or the closest equivalent), re-fertilisation (or slow release applied at time of planting), weed control (estimated number of weed-free years), initial stocking, and tree age at time of measurement. This compilation produced 1726 records of growth and associated information. Each record contained (in the order in which they appear in the database):

(i) an experiment identifier, consisting of an alphabetic conservancy code and a number;

(ii) time since planting until each set of measurements was conducted (in years);

(iii) dummy variable (1=yes, 0=no) to denote ripping;

(iv) dummy variable to denote discing;

(v) estimated number of years of weed control;

(vi) number of grams per tree of elemental phosphate applied after planting;

(vii) number of grams per tree of elemental nitrogen applied after planting;

(viii) dummy variable denoting whether the diameter measurements were at breast height (1) or at root collar diameter (0);

(ix) number of height measurements;

(x) mean height of all trees at the time represented by the record;

(xi) mean diameter (dbhob or root collar)[3] of all trees;

(xii) minimum height;

(xiii) minimum diameter (dbhob or root collar)[3];

(xiv) maximum height;

(xv) maximum diameter (dbhob or root collar)[3];

(xvi) height sums of squares;

(xvii) diameter (dbhob or root collar)[3] sums of squares;

(xviii) height kurtosis coefficient;

[3] Variables in this field contained either dbhhob or root collar diameter measurements, depending on where the measurements had been made. Variable viii denoted which was which.

(xix) diameter (dbhob or root collar)[3] kurtosis coefficient;

(xx) height skewness coefficient;

(xxi) diameter (dbhob or root collar)[3] skewness coefficient;

(xxii) number of missing height measurements;

(xxiii) dummy variable denoting whether the stand had been thinned at the time of measurement;

(xxiv) sum of the height measurements;

(xxv) sum of the diameter (dbhob or root collar)[3] measurements;

(xxvi) sum of height and diameter (dbhob or root collar)[3] cross products;

(xxvii) number of diameter (dbhob or root collar)[3] measurements;

(xxviii) dummy variable denoting whether the stand had been pruned at the time of measurement;

(xxix) dummy variable denoting whether the stand had been either refertilised (or the fertiliser had been of a slow release type, such as rock phosphate);

(xxx) number of stems immediately after planting (within the treatment, not per hectare);

(xxxi) proportion of trees planted which were surviving at the time of measurement;

(xxxii) mean height immediately after planting;

As each record was added, the height and diameter (dbhob or root collar) maxima and minima were compared with data from plots with similarly sized trees. In some cases, unusually large or small values led to a re-examination of the original data sheets, and to the correction of punching errors in the raw data files, followed by a recomputation of the complete record.

b) Data used for initial growth modelling. Of the 60 experiments summarised, 27 were used to build a size distribution model of radiata pine between ages 0 and 5 in the Central North Island. Only three of the remainder were located in the Central North Island region, and these were later used for model validation. The locations of the experiments are shown in Figure V.1. The experiments were all randomised complete block designs, containing 10 trees per plot, except for one, which contained 5 trees per plot. A separate catalogue of these experiments was created which specified, for each plot, altitude, longitude, latitude, distance from the sea, average annual rainfall (at the nearest New Zealand Meteorological Service (NZMS) rainfall station), average annual temperature (at nearest NZMS meteorological station), soil type, soil fertility (as rated by the Department of

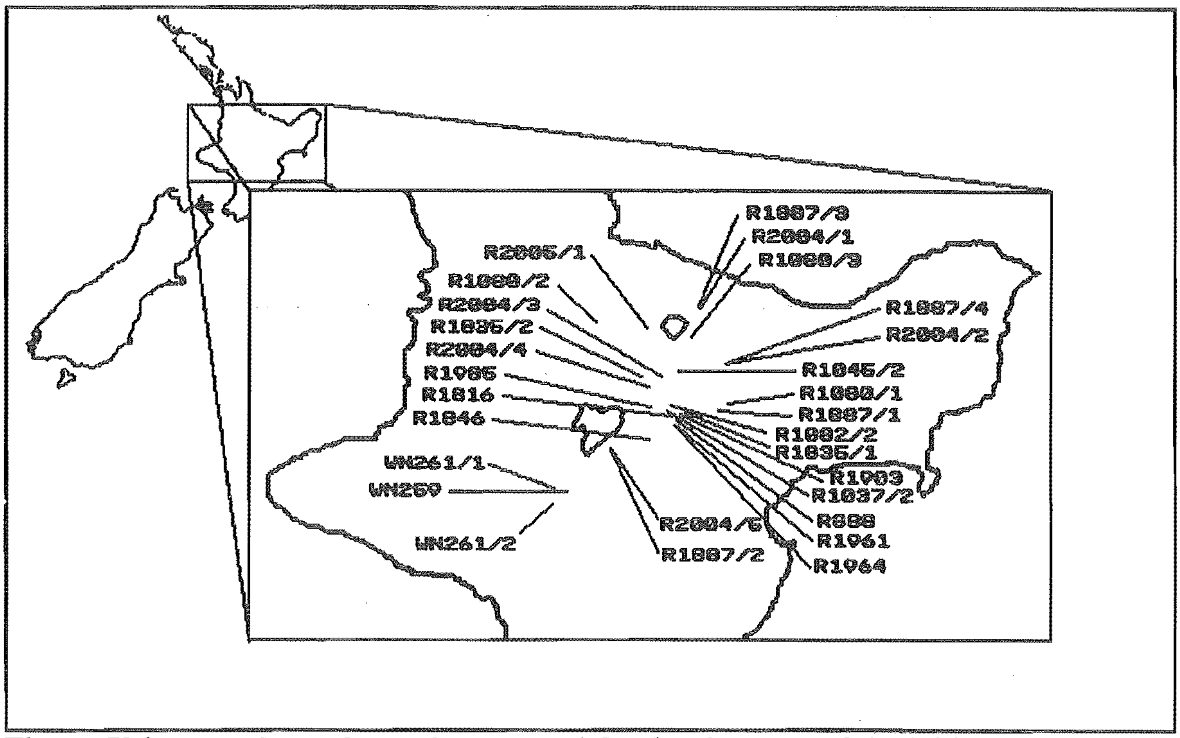

Figure V.1 - Locations of experiments used for development of the initial growth model for the Central North Island Region of New Zealand.

Scientific and Industrial Research (1954, 1968) Soil Bureau (DSIR)), soil drainage (DSIR), response to phosphate (DSIR), total nitrogen (DSIR), percent clay (DSIR), cation exchange capacity (DSIR), pH (DSIR), and the nature of the topography (flat, medium slope, high slope). All the soils were of pumice origin, loamy or gravelly sands, and well drained. Relevant site variables, treatments, and times of measurements are shown in Table V.1.

Measurements taken after pruning or thinning were not included in the analysis, as too few post-pruning and -thinning measurements were available, and it was considered that these effects would add complications which could be the topic for other studies.

Two of the experiments were designed to determine the effects of different initial spacings. The total range of spacings represented overall was 200 to 4444 stems/ha.

Table V.1 - Experiments used for analysis of initial growth

Experiment I.D.	Altitude (m)	Factor levels			Age when measured		
		Weed Control	Cultivation	Fertilisation	Height	Root Collar diameter	dbhob
Wn259	951	1	1,0	0	0-4,6,7	0-4,6	7
Wn261/1	1062	1	1,0	N*P,0	0-2,4,6	0-2,4,6	
Wn261/2	686	1	1,0	N*P,0	0-2,4	0-2,4	
R888	604	1	1,0	0	0-3	0-3	
R1037/2	632	1	1	0	0-4	0-4	
R1045/2	532	1	1,0	0	0-3	0-3	
R1080/1	503	1	0	N+P,0	0-5		4,5
R1080/2	168	1,0	0	N+P,0	0-5		4,5
R1080/3	305	1,0	0	N+P,0	0-5		4,5
R1082/2	625	1	1,0	0	0-3	0-3	
R1816	603	1	1	0	0-3	0-3	
R1835/1	591		1,0	N+P,0	0-5	0-3	4,5
R1835/2	457	1,0	1,0		0-5	0-3	4,5
R1846	762	1,0	1,0	N+P,0	0-6	0-5	6
R1887/1	457	1	0	0	0-4		4
R1887/2	590	1	0	N+P	0-4		4
R1887/3	300	1	0	0	0-3		
R1887/4	435	1	0	0	0-6		5-7
R1903	600	1	1	0	0-3	0-3	
R1961	640	1	1,0	0	0-3,5	0-3,5	
R1964	640	1	1,0	N*P,0	0,2,4	0,2,4	
R1985	615	1	1,0	N*P,0	0,2,4	0,2,4	
R2004/1	370	1	0	0	0-2		
R2004/2	430	1	0	0	0-3		
R2004/3	370	1	0	0	0-2		
R2004/4	350	0	1	0	0-4		
R2005/1	360	1	0	0	0-3		

Mean rainfall at the closest rainfall stations varied between 895 and 2019 mm/annum, while mean annual temperatures at the closest meteorological stations ranged between 7.8 and 12.5 degrees Celsius. Planting in all experiments on potentially frosty sites had been conducted towards the ends of planting seasons.

2) Modelling methodology

The modelling tools and methodology employed were essentially the same as those outlined for the analysis of Nelder experiments (Chapter IV). The estimation of coefficients for the initial growth models proceeded from the simplest models to more complex ones. At each stage, plots of residuals against likely additional independent variables were examined for correlations, and as each independent variable was added, its interactions with other variables were tested.

3) Analyses of individual site preparation experiments

Lack of independence due to repeated measures meant that modelling with the complete Central North Island data set could not be used as a vehicle for testing hypotheses about differences in height, diameter (dbhob or root collar) and survival due to site preparation treatments. Analyses of individual site preparation experiments were therefore collated,[4] or conducted where necessary, to determine which independent variables denoting site preparation were likely to be useful in models for the entire region.

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[4] In many instances, analyses had been conducted by experiment designers, and these were available in the form of unpublished reports. The analyses were inspected to ensure that appropriate statistical models had been employed.

14 of the 27 experiments used for modelling contained direct comparisons between cultivation, weed control, and/or fertilisation treatments in designs which enabled valid statistical tests of differences in height, diameter, and/or survival between these treatments to be performed for any one year of measurement. The remainder either had inadequate replication for valid hypothesis testing, or were designed to test other treatments.

All of the 14 experiments were of randomised complete block design, and 6 included factors in a split plot arrangement. In these latter experiments, plots of cultivation treatment were split into alternative weed control and/or fertilisation treatments. All experiments were subjected to analyses of variance, with one analysis for each year's measurements of height and dbhob or root collar diameter. For each experiment, one of the following generalised models was used, depending on the exact experimental design:

$$X_{ijk}=\mu+M1_i+M2_j+(M1*M2)_{ij}+B_k+\epsilon_{ijk} \tag{V.1}$$

$$\begin{aligned} X_{ijkl}=\mu+M_i+B_j+\epsilon_{ij}+T1_k+T2_l+(M*T1)_{ik}+(M*T2)_{il} \\ +(T1*T2)_{kl}+(M*T1*T2)_{ikl}+\delta_{ijkl} \end{aligned} \tag{V.2}$$

where M, M1 or M2 denote mainplot treatments, and T1 and T2 denote subplot treatments. In some cases, only one mainplot or subplot treatment was incorporated in the experimental layout, and the terms containing the second treatment effect were therefore not included in the model.

Results from the individual experiments were tabulated. In five cases the results were obtained from published papers, in another four from internal reports written by members of the Soils and Site Productivity section at the New Zealand Forest Research Institute, and the remainder were analysed directly from raw data.

4) A model of initial growth for the Central North Island

The analyses of individual site preparation experiments indicated treatments which could apparently be used as independent variables in a regional model of initial growth. Data from all 27 experiments were used to build models of survival, mean height and basal area/ha.

a) Seedling survival. In a few cases, destructive sampling had been undertaken within plots. An adjustment to the denominator (normally N_0, the initial stems per plot) was required when survival proportions (S) were calculated for years after the date of sampling. The adjustment used was as follows:

$$N_{0n}=N_{0o}\frac{(N_{TD}-D)}{N_{TD}} \tag{V.3}$$

Where N_{0n} = new denominator (S_T then became N_T/N_{0n}); N_{0o} = old denominator (initial number of trees in plot if there was no previous destructive sampling); N_{TD} = number of trees in the plot immediately before destructive sampling; and D = number of trees destructively sampled. This assumed that destructively sampled trees had a likelihood of dying equivalent to those trees which were not sampled.

Several survival (S=survival proportion) functions were tried in difference form, employing both proportions and absolute number of stems. An arcsine square root transformation was employed in all analyses involving proportions.

(i) Anamorphic forms:

$$S_2=S_1e^{(-\alpha(T_2^{\beta}-T_1^{\beta}))} \tag{V.4}$$

$$S_2=S_1\left(\frac{T_1+1}{T_2+1}\right)^{\alpha}e^{-\alpha(T_2-T_1)} \tag{V.5}$$

$$S_2=S_1^{\left(\frac{T_2+1}{T_1+1}\right)^{\alpha}} \tag{V.6}$$

$$S_2=S_1\left(\frac{T_2+1}{T_1+1}\right)^{\alpha} \tag{V.7}$$

In each case the hypothesis was that α was a linear function of altitude, three dummy variables (weed control, cultivation, and site flatness), and their interactions. Function V.4 was also tested with "weed presence" substituted for the weed control dummy variable (i.e., if stand age for a given record was greater than the estimated duration of weed control, then weeds were assumed to be present). The yield form of function V.4 was also evaluated:

$$S_T=e^{\alpha T^{\beta}} \tag{V.8}$$

(ii) Polymorphic forms:

$$S_2 = S_1 e^{\beta(T_2 - T_1)} + \alpha(1 - e^{\beta(T_2 - T_1)}) \tag{V.9}$$

$$S_2 = (S_1^{-\beta} + \alpha(T_2^{\gamma} - T_1^{\gamma}))^{-\frac{1}{\beta}} \tag{V.10}$$

b) Mean height. The following function was fitted to each treatment within each experiment:

$$\bar{h}_T = \bar{h}_0 + \alpha T^{\beta} \tag{V.11}$$

Where h_0 = mean height immediately after planting.

The regression coefficients pertaining to each treatment within experiments were then plotted against the following variables:

(i) altitude;

(ii) weed control;

(iii) ripping;

(iv) discing;

(v) phosphate fertilisation;

(vi) nitrogen fertilisation;

(vii) site flatness;

(viii) distance from the sea;

(ix) average rainfall at the nearest meteorological station.

Subsequently, equation V.11 was fitted to the entire data set, using proc NLIN, with parameters as linear functions of altitude and other combinations of the listed independent variables. The generalised model used was:

$$h_T=h_0+(A_0+A_1V_1+...+A_nV_n)T^{B_0+B_1V_1+...B_nV_n} \qquad (V.12)$$

where $V_1..V_n$ were independent variables and their interactions, and $A_0..A_n$ and $B_0..B_n$ were estimated coefficients. A model was first estimated with only altitude, and then variables were subsequently added one by one, followed by their interactions if the estimated coefficients were significantly different from zero.

The difference form of V.12 was also tested, using likely useful independent predictors determined from the analysis with the function in yield functional form.

c) Basal area. Basal area per hectare was calculated for each treatment within each experiment, and these values were plotted against the independent variables listed in section V.1.4.b, as well as against initial stocking.

The following function was fitted to all data, with the α regression coefficient as a linear function of altitude:

$$G_T=\alpha N_0T^{\beta} \qquad (V.13)$$

Another function was also examined:

$$G_T=(A_0+A_1V_1+...A_nV_n)N_0T^{\beta}-N_0k \tag{V.14}$$

Independent variables listed in section V.1.4.b were tried, beginning with a model containing simply altitude, and adding variables to form more complicated models.

Regression coefficients in the mean height function (V.11) estimated for each individual treatment within each experiment were matched with basal area data from each individual treatment within each experiment, and the time at which mean height equalled 1.40 m $T_{G=0}$ was estimated for each record from:

$$T_{G=0}=\left(\frac{1.4-\bar{h}_0}{\alpha}\right)^{\frac{1}{\beta}} \tag{V.15}$$

Using these estimates of $T_{G=0}$, the following function was fitted, with combinations of, and interactions between, the independent variables listed in section V.1.4.b:

$$G_T=(A_0+A_1V_1+...+A_nV_n)N_0T^{\beta}-(A_0+A_1V_1+...+A_nV_n)N_0T^{\beta}_{G=0} \tag{V.16}$$

In an attempt to utilise available root collar diameter data, the following function was fitted with the same independent variables as for the best fit of function V.16:

DBH and RCD were dummy variables indicating that either dbhob or root collar

$$G_T = \frac{\alpha N_0 T^{\beta}}{DBH + RCD * \gamma} - DBH(\alpha N_0 T^{\beta}_{G=0}) + RCD(G_0) \tag{V.17}$$

where

$$\alpha = (A_0 + A_1 V_1 + ... + A_n V_n)$$

diameter, respectively, had been measured for any given record, and G_0 was the root collar cross sectional area immediately after planting.

d) Distributions. In order to fit models from which parameters could be recovered for representing distributions to describe frequencies per unit area of height and dbhob at any age, functions of the same form as V.12 were estimated with maximum height and height variance as dependent variables. Maximum dbhob was estimated with the following function:

$$Y_T = \alpha T^{\beta} - \alpha T^{\beta}_{Y=0} \tag{V.18}$$

where

$$\alpha = (A_0 + A_1 V_1 + ... + A_n V_n)$$

Dbhob variance was estimated as a linear function of the independent variables listed in section V.I.4.b. and stand age.

The probability density function found to represent these distributions best was the reverse Weibull (Kuru *et al.* 1991). Predicted distributions were compared with those observed in the raw data, and appropriate percentiles of the extreme distributions were arrived at through trial and error.

e) Limited validation. Data from three additional experiments which had not been used to build the models just described were also available. The experiments were in Kaingaroa Forest, compartment 455 (611 m altitude, weed control, no cultivation), compartment 552 (611 m altitude, weed control, ripping and mounding), and compartment 542 (700 m altitude, weed control, no cultivation). They were intended to compare alternative lifting and root trimming treatments, in which one treatment per experiment was useful for validation purposes. Annual height measurements from ages 0 to 4 were available from all experiments. Dbhob measurements were available from only compartment 455 at age 4. This validation set is obviously limited but provides some validation capability until further data become available.

The mean height was calculated for each age, and the height distribution at age 4 was plotted. These were graphically compared with statistics predicted by the models described above for each site. The distribution of dbhob in compartment 455 was also graphically compared with the predicted distribution.

V.2. RESULTS

1) Analyses of individual site preparation experiments

A summary of the results of hypothesis testing in site preparation experiments is shown in Table V.2. In all cases, the null hypothesis was that there was no difference in survival, height, or diameter at the oldest pre-thinning and pre-pruning age of measurement within each experiment. In most cases, the null hypotheses were rejected at the $p<0.01$ level, but Table V.2 includes some effects where the hypotheses were rejected at only the $p<0.05$

level.

The results for initial growth modelling can be summarised as follows:

(i) weed control consistently resulted in improved height and diameter growth and improved survival in some of the experiments;

(ii) cultivation often resulted in improved survival, and sometimes in improved height and diameter growth. Ripping and mounding resulted in improved growth more consistently than did ripping alone;

(iii) fertilisation produced improvements in growth in only a minority of the experiments, and had no apparent influence on tree survival;

(iv) interactions were significant in only two instances, one between weed control and cultivation, and the other between weed control and fertilisation.

Table V.2 - Summary of hypothesis testing of site preparation effects from individual experiments.

Experiment	Age	Rip	Mound	Weed Control	P Fert.	N Fert.	P+N Fert.	Reference
WN259	6	n.s.	H D					EGM
WN261/1	6		H D S		H D	H D		SSP
WN261/2	6	n.s.			n.s.	n.s.		SSP
R888	3		H D S					EGM
R1080/1	5						D	GWp
R1080/2	5			H D S			n.s.	GWp
R1080/3	5			H D			n.s.	GWp
R1082/2	3	n.s.						EMp
R1835/1	5	S	n.s.				n.s.	EGM
R1835/2	5	H D S	H D S	H D				EGM
R1846	5			H D S			n.s.	EGM
R1961	5	H S						EMp
R1964	4	H S			n.s.	n.s.		SSP
R1985	4	H D	n.s.		n.s.	H D		SSP

Notes:

Age=age of trees at which measurements were taken

H=significant height increase
D=significant diameter increase (root collar diameter or dbhob)
S=significant survival increase
n.s.=no significant differences
blank=not tested

Where an experiment contained both ripping and mounding treatments, and a significant mounding effect is indicated, the mounding treatment was an improvement on, and significantly different from the ripping treatment.

SSP= Analysis recorded in Forest Research Institute Project records
GWp= Analysis published (West 1984)
EMp= Analysis published (Mason & Cullen 1986a)
EGM= Analysis performed by E.G. Mason

No exact quantitative comparison of the magnitudes of the effects could be made without modelling, as the hypotheses were tested at ages which varied from experiment to experiment. However, the effects of weed control on height and diameter growth were generally much larger and occurred more consistently than the effects of cultivation, which, in turn, were generally larger and more consistent than the effects of fertilisation.

2) A model of initial growth for the Central North Island

a) Survival. The smallest residual mean squares and the least biased residuals were produced by fitting functions V.4 and V.8. The rate of mortality diminished with time in most plots, conforming to the assumptions outlined in chapter III, but mortality was higher during later years than during the first in one experiment in plots where weeds were not controlled, causing the very uneven residual distribution shown in Figure V.2.

In general, the anamorphic functions represented early survival better than the polymorphic ones. The α parameter of function V.8 was related to several factors describing site quality and associated treatments. Survival decreased with altitude but the interaction between altitude and weed control was significant, with weed control improving survival to a greater extent at higher altitudes. The cultivation effect was independent of other factors, with ripping and/or mounding increasing survival.

There was an indication that mortality was greater on flat sites than on sloping sites, but data from trees grown on sloping ground were available only from high altitude sites, and including flatness as a variable in the model resulted in a poorly behaved pattern at lower

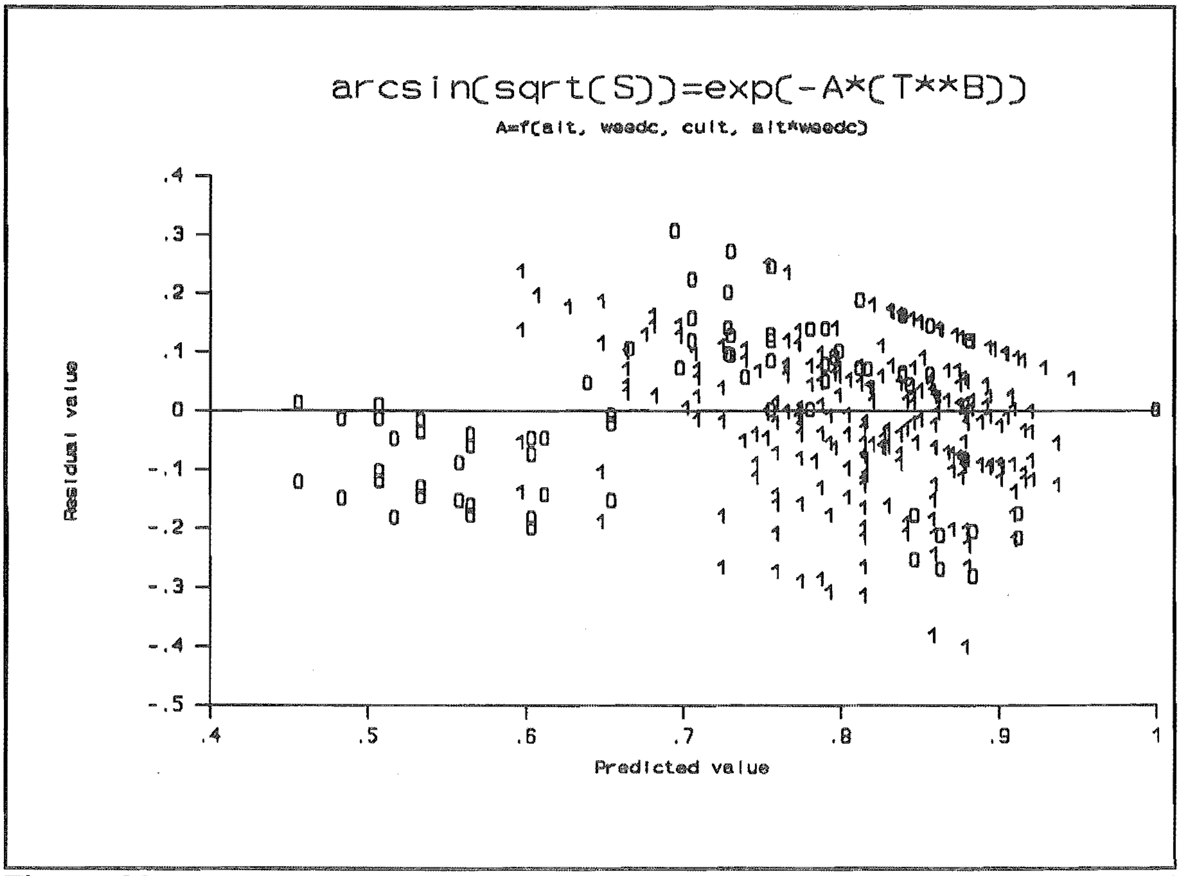

Figure V.2 - Residual vs predicted values from the survival model selected. 1=weed control, 0=no weed control.

altitudes. For this reason, flatness was not retained in the model finally adopted, but some recognition of such a possible effect may be needed in future studies.

b) Height. Function V.11 fitted the data very well. Figure V.3 shows the residual distribution for all observations when a separate function was fitted for each treatment within each experiment. Most of the residuals were less than ±10 cm, and none exceeded ±25 cm. Plots of the model parameters vs. altitude (Figure V.4) showed a declining linear relationship up to 760 m, and a flattening beyond 760 m.

Multi-linear analyses showed that the α parameter of function V.11 was related to altitude, weed control, mounding, and the altitude * weed control interaction. The ß

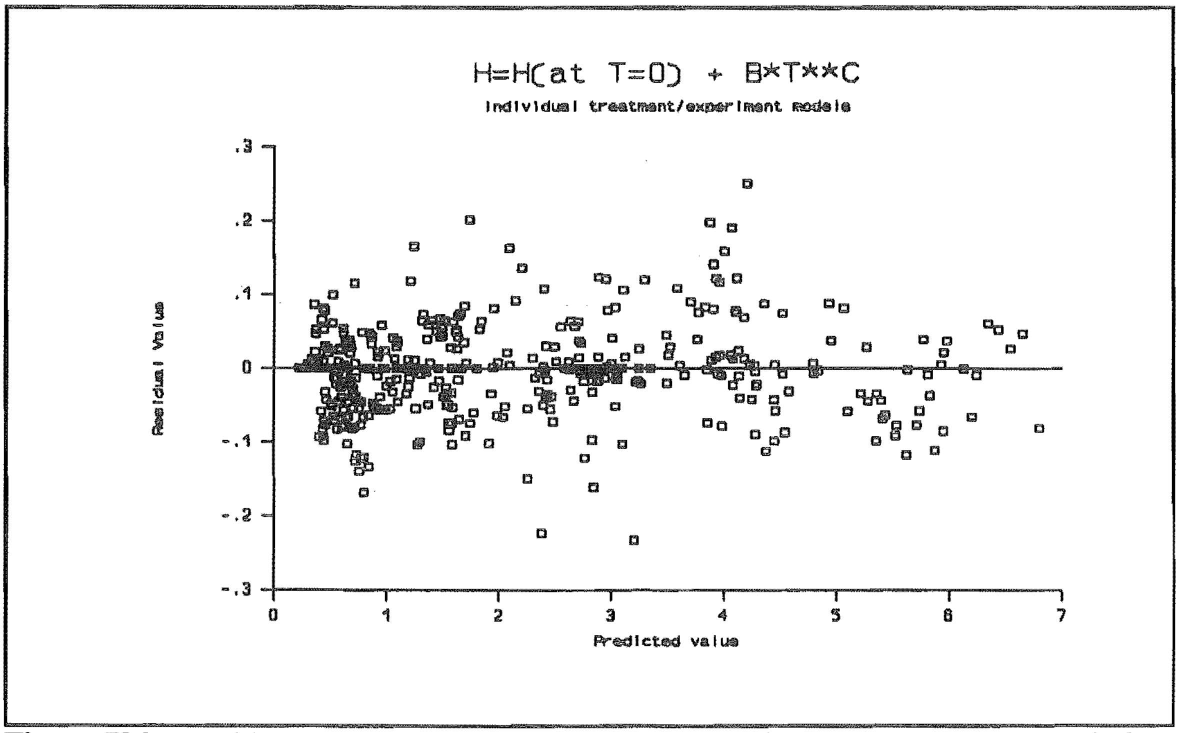

Figure V.3 - Residual pattern from mean height models fitted to each treatment within a plot individually.

parameter was related to altitude and weed control.

Results for experiment R2004/2 were anomalous. Parameters estimated for the height model within this plot were not only outside the range expected for the location and treatments within the experiment, but were also an unusual combination of α and ß parameter values. Inquiry with the controller of the experiment (M. I. Menzies, Scientist at the NZ Forest Research Institute, pers. comm.) revealed that severe boron deficiency had been observed in the experiment after two years of growth, and the entire experiment had been fertilised with ulexite. The experiment was therefore excluded from all further analyses.

Two other apparently significant independent variables were found in the analysis, but each was subsequently dropped. Distance of the experiment from the sea was often significant, but highly correlated with altitude. Height growth was depressed on flat sites, but

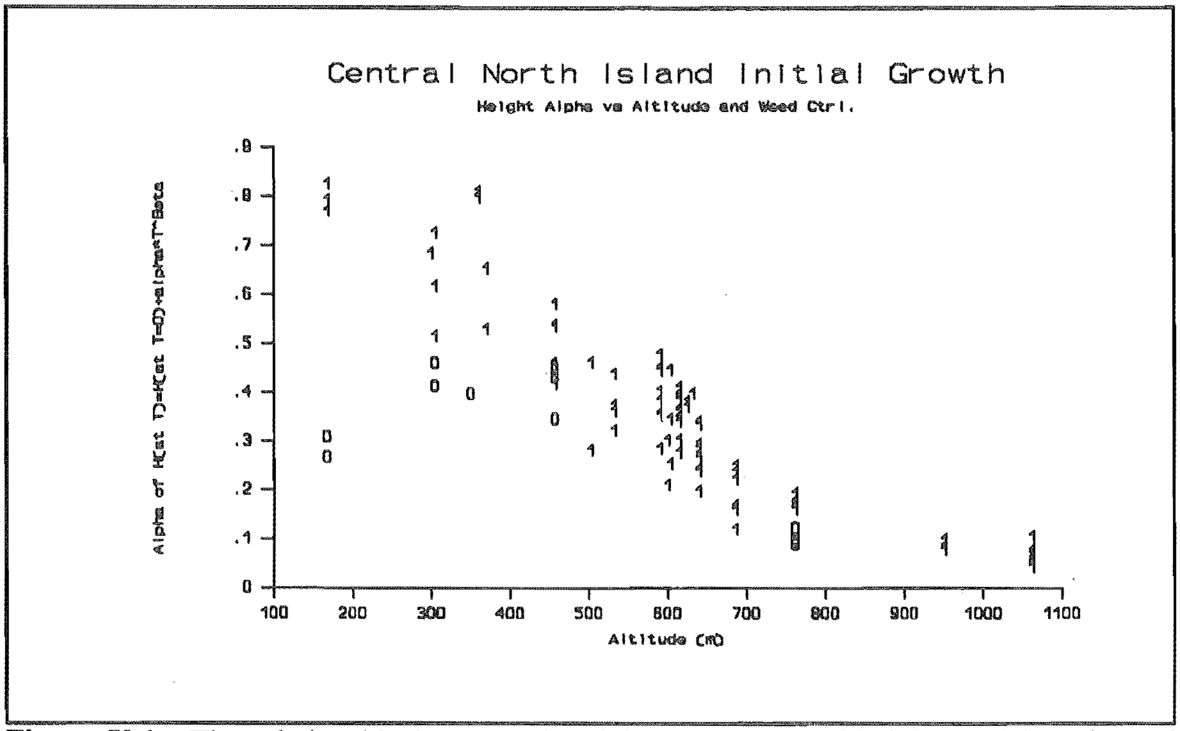

Figure V.4 - The relationship between the alpha parameters of height models estimated for each treatment/experiment and altitude. 1=weed control; 0=no weed control.

retention of this discrete variable in the model could not be justified for the reasons outlined in section V.2.2.a.

A model was fitted using procedure NLIN for function V.11, with α as a function of altitude, weed control, mounding and the weed control * altitude interaction, and with β as a function of altitude and weed control. Experiments above 760 m altitude were excluded, as the relationship between altitude and the α parameter had been shown to be non-linear above this altitude (Figure V.4), and no formulation was found that could represent mean height both above and below 760 m altitude without biased residual distributions. Most of the residuals were within ±0.5 m of the predictions (Figure V.5), and all except one were within ±1 m. Height increased with weed control, mounding, and diminishing altitude. The effect of weed control on height was greater at lower altitudes, but there was considerable variation associated with the plots subjected to differential weed competition (Figure V.4).

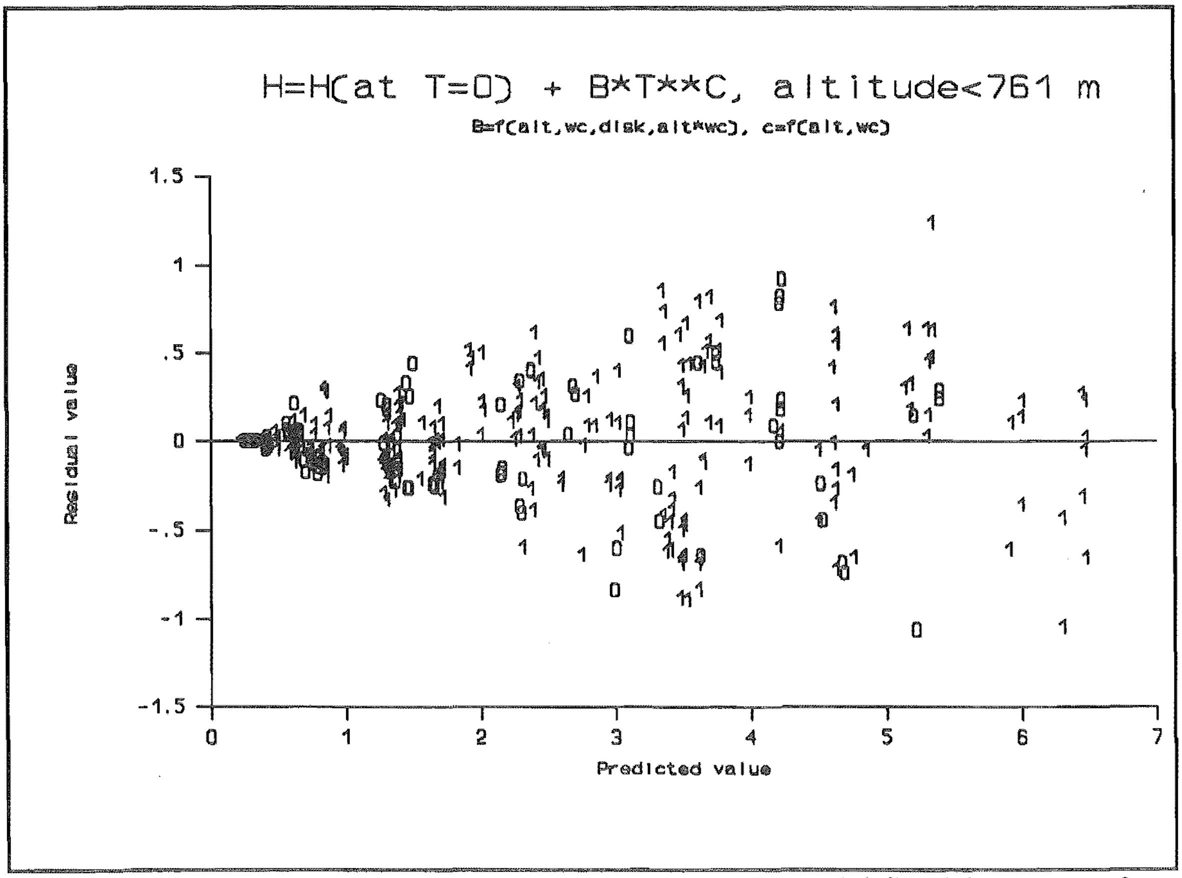

Figure V.5 - Residual vs predicted values for mean height model fitted for all data from experiments below 761 m altitude. 1=weed control, 0=no weed control.

Transformations of altitude values were attempted, in order to incorporate the experiments above 760 m in the model. The inverse of altitude and the square of altitude proved the most promising, but both resulted in poor estimations at lower altitudes (Figure V.6).

Function V.12 was also fitted in difference form (with the same independent variables), using only the smallest growth intervals. Parameter values obtained were virtually identical to those obtained from a yield form, except that some of the parameters had confidence intervals which encompassed zero.

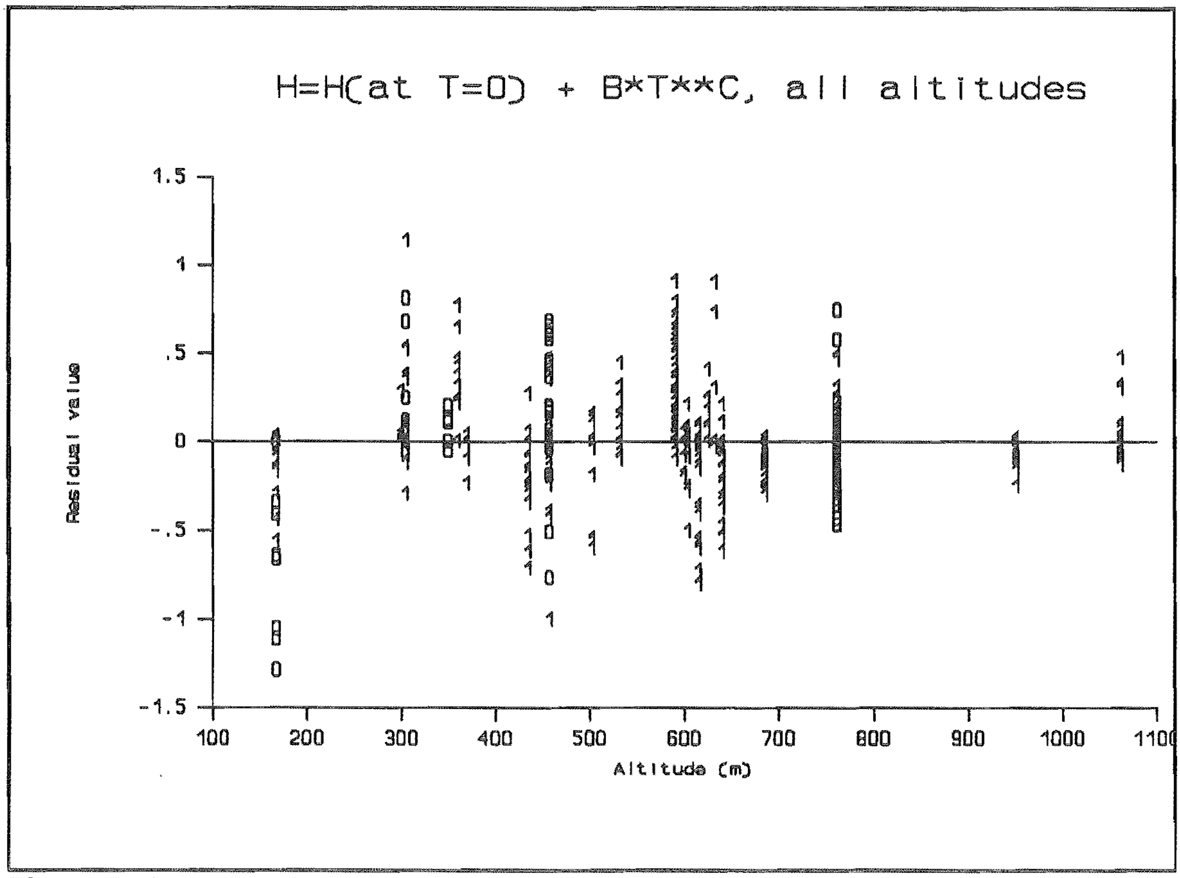

Figure V.6 - Residual vs altitude for mean height model estimated from all data. 1=weed control, 0=no weed control. B=f(altitude, weed control (WC) , discing, and altitude * WC), C=f(altitude, WC).

Controllers of the experiments had generally guessed the number of weed-free years expected of their control methods. These guesses were used to fit a model in difference form sensitive to re-introduction of weeds in plots where weed control had been implemented. The parameters associated with weed control in this model were small and insignificant.

In summary, function V.12 fitted the data very well, with altitude, weed control, discing, and the weed control*altitude interaction being useful predictor variables. Predictions of growth would be more precise in the absence rather than in the presence of weeds. Data above 760 m altitude were excluded from the analysis, because their inclusion resulted in biased models. Initial height growth above 760 m in the Central North Island region should be a topic for further research.

c) <u>Basal area</u>. The best fitting basal area function was V.16. The α parameter of this function was related to the natural logarithm of altitude, weed control, and diamonium phosphate (DAP) fertilisation * weed control. As the last factor was not consistently significant in the analyses of individual experiments, the function was fitted without DAP fertilisation * weed control as well. The residuals were distributed within ±5 m^2/ha of the model (Figure V.7).

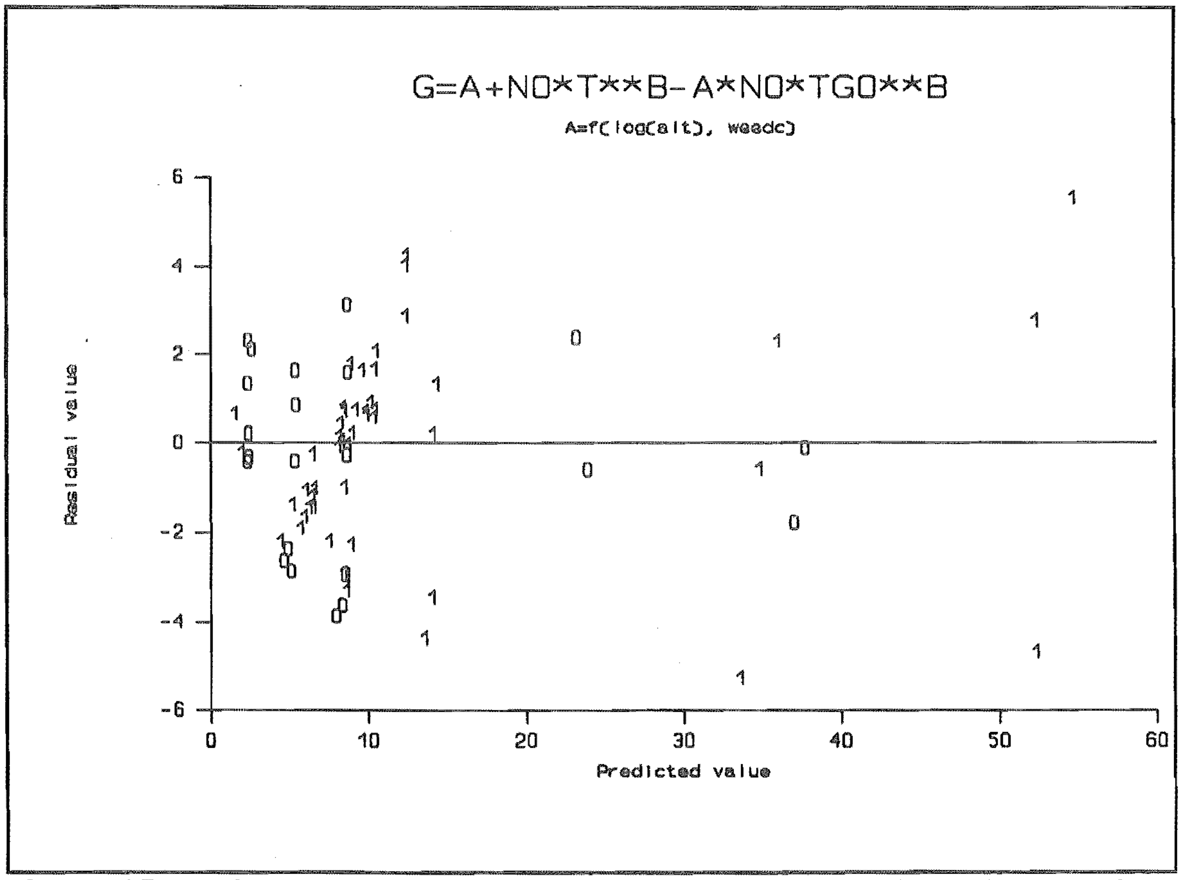

Figure V.7 - Residual vs predicted values for basal area/ha model. 1=weed control, 0=no weed control.

Function V.17 was fitted to all records with diameter measurements either at breast height or at root collar. Independent variables included those for the model fitted to basal area at breast height only, plus mounding, weed control * altitude, and altitude squared. This last-named variable was needed because data above 760 m were included, and the relationship between basal area and altitude (for equivalent stocking) was no longer linear. Plots of the residuals (figure V.8) showed that the fit was poorer for the basal area at breast height measurements than function V.16.

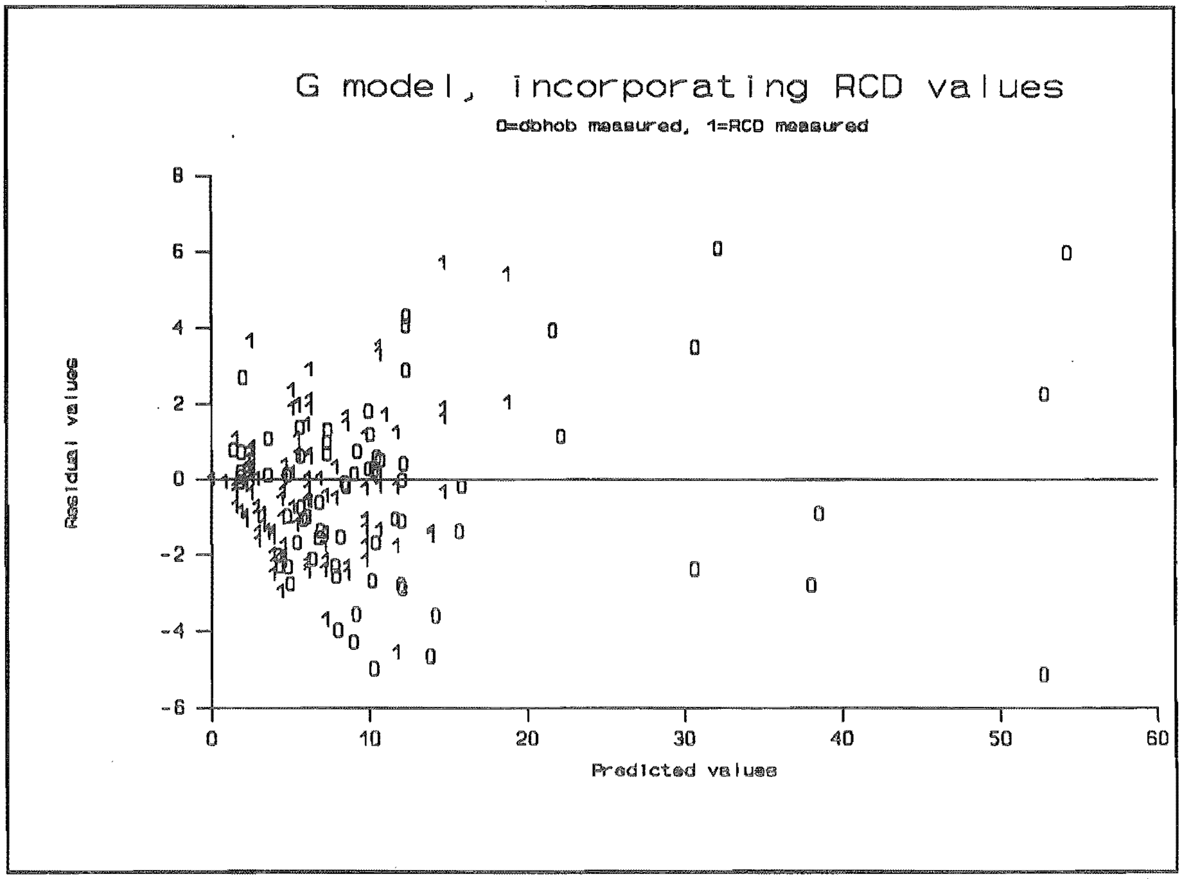

Figure V.8 - Residual vs predicted values for the basal area/ha model estimated with values calculated from both dbhob and RCD measurements. A=f(log(altitude) (ALT), weed control (WC), ALT*WC, disk).

To summarise, adjusting the intercept of the basal area function so that the model was compatible with the height model resulted in reasonable estimates of the basal area growth of very young stands. Weed control, initial stocking and the natural logarithm of altitude, were included as independent variables. The DAP fertilisation * weed control factor was not expected to have an influence, and when included, its effect on the model was small.[5] This model was less precise overall than the height model, because fewer dbhob data than height data were available. An attempt was made to use root collar diameter and dbhob data jointly in a function which implied a linear relation between basal area and root collar cross sectional area, but the resulting model was less precise than the model estimated from basal area data only.

d) Height distribution models. Maximum height was well represented by function V.12, with residuals all distributed within ±1.5 m of the model, and most within ±1 m (Figure V.9). Independent variables were altitude, weed control, mounding, and the altitude * weed control interaction for the equivalent of the α parameter of function V.11. The ß parameter was a function of altitude and weed control.

Height variance was also well represented by a function of the same form as V.12, with parameters related to altitude and weed control. The effect of weed control on height variance was particularly evident, with weed competition causing an increase in variation between trees.

The percentile of the extreme distribution employed for predictions of maximum height was 96%.

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[5]. The model software has been provided with a set of parameters which do not include the effect of DAP fertilisation * weed control. However, if users wish they can use a model incorporating this factor by renaming file "parms.cni" (the parameters used by the program) and then renaming "pfwcprms.cni" (parameters including the DAP effect) to "parms.cni".

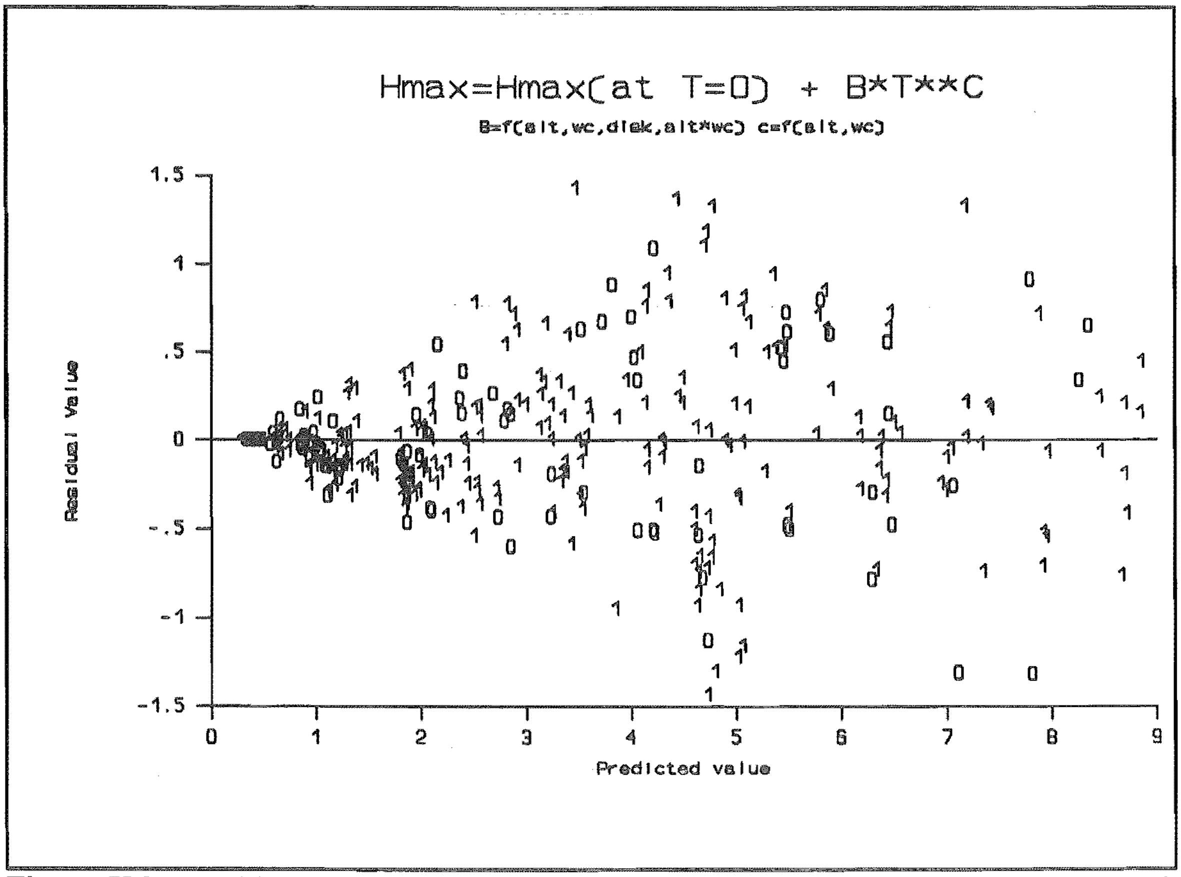

Figure V.9 - Residual vs predicted values for maximum height model. 1=weed control, 0=no weed control.

e) Diameter distribution models. Models of maximum dbhob, mean dbhob, and dbhob variance were much less precise than those of height, owing to the much reduced dbhob data set. For maximum dbhob, the α parameter of function V.17 was related to the logarithm of altitude. Weed control was also included, for compatibility with the model of basal area. With two exceptions, the residuals were all distributed within ±2 cm of the model (Figure V.10).

Mean dbhob was also represented with function V.17, and the α parameter was related to log(altitude), weed control, and log(altitude) * weed control. Mean dbhob was not used for distribution representation, for reasons outlined below.

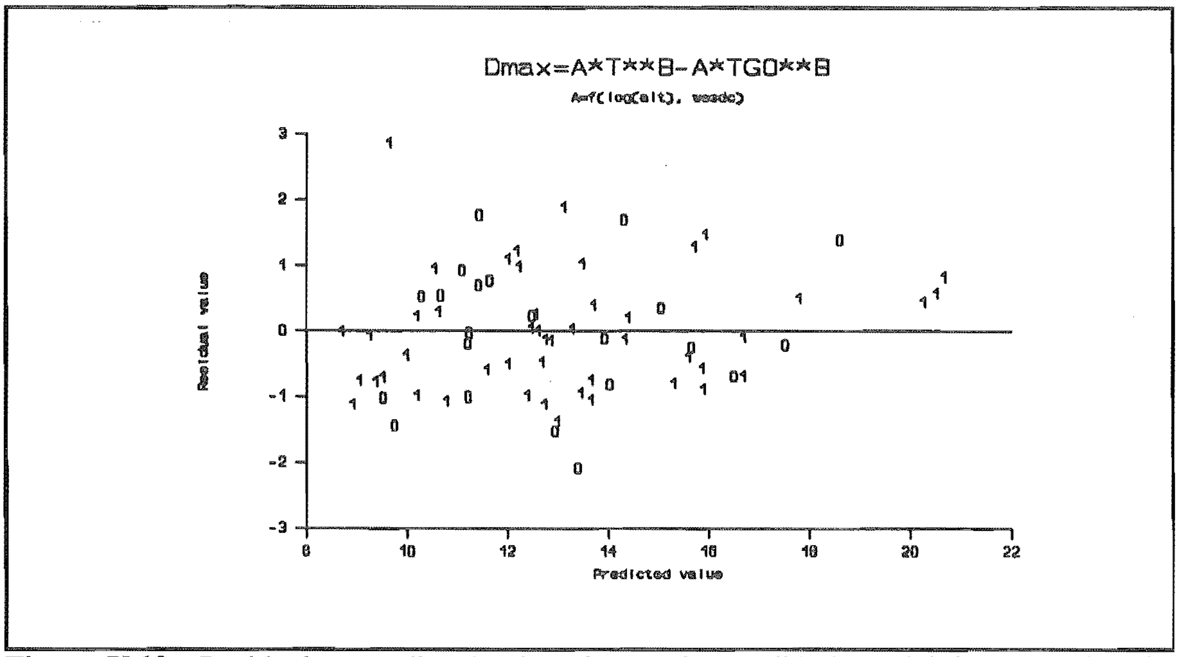

Figure V.10 - Residual vs predicted values for maximum dbhob model, incorporating the time when maximum height reaches 1.4 m (TG0). 1=weed control, 0=no weed control.

Dbhob variance was represented by a multi-linear function. It decreased with altitude and weed control, and increased with age and altitude*weed control. Dbhob variance decreased with initial stocking, but, although the parameter confidence interval excluded 0, no sound biological reason for the correlation was evident, so initial stocking was not used in the model finally adopted (Figure V.11).

When the diameter distribution parameters were recovered, it was clear that more consistent representations of the distributions were obtainable by employing models of basal area, survival, maximum dbhob and dbhob variance than when dbhob variance was recovered from the basal area and mean dbhob models.

The percentile of the extreme distribution employed for predictions of maximum dbhob was 95%.

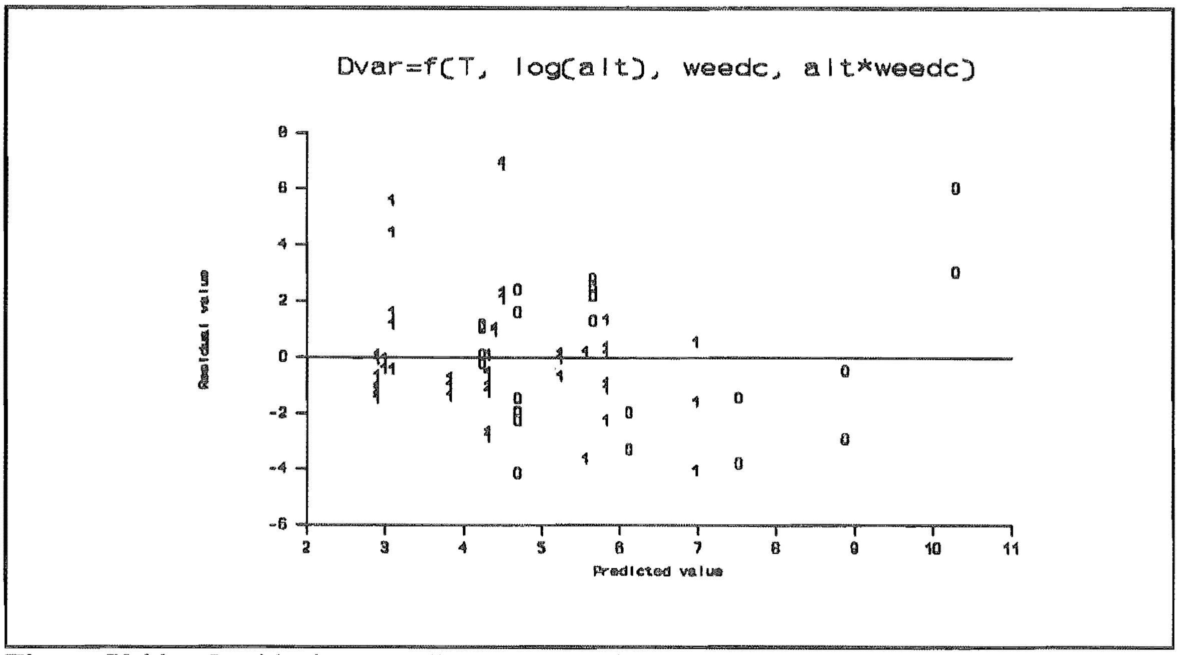

Figure V.11 - Residual vs predicted values for multi-linear model of dbhob variance. 1=weed control, 0=no weed control.

f) Software. The best fitting functions were represented in an MS-DOS personal computer program written in PDC-PROLOG (Prolog Development Centre 1990). Parameters of the height and diameter distributions were recovered from predicted stand statistics as described in chapter II.

The program was designed with a graphical user interface which enables users to compare visually the predicted crop responses to alternative establishment strategies on different sites (Figure V.12), and to extract ASCII files with predicted responses in numerical form.

g) Limited Validation. Graphs of predicted and observed mean height, height distribution, and dbhob distribution are shown in figures V.13, V.14, and V.15. Whilst the validation data set was extremely limited, it was encouraging that the predictions of mean height and height distribution were very close to those observed. The diameter distribution

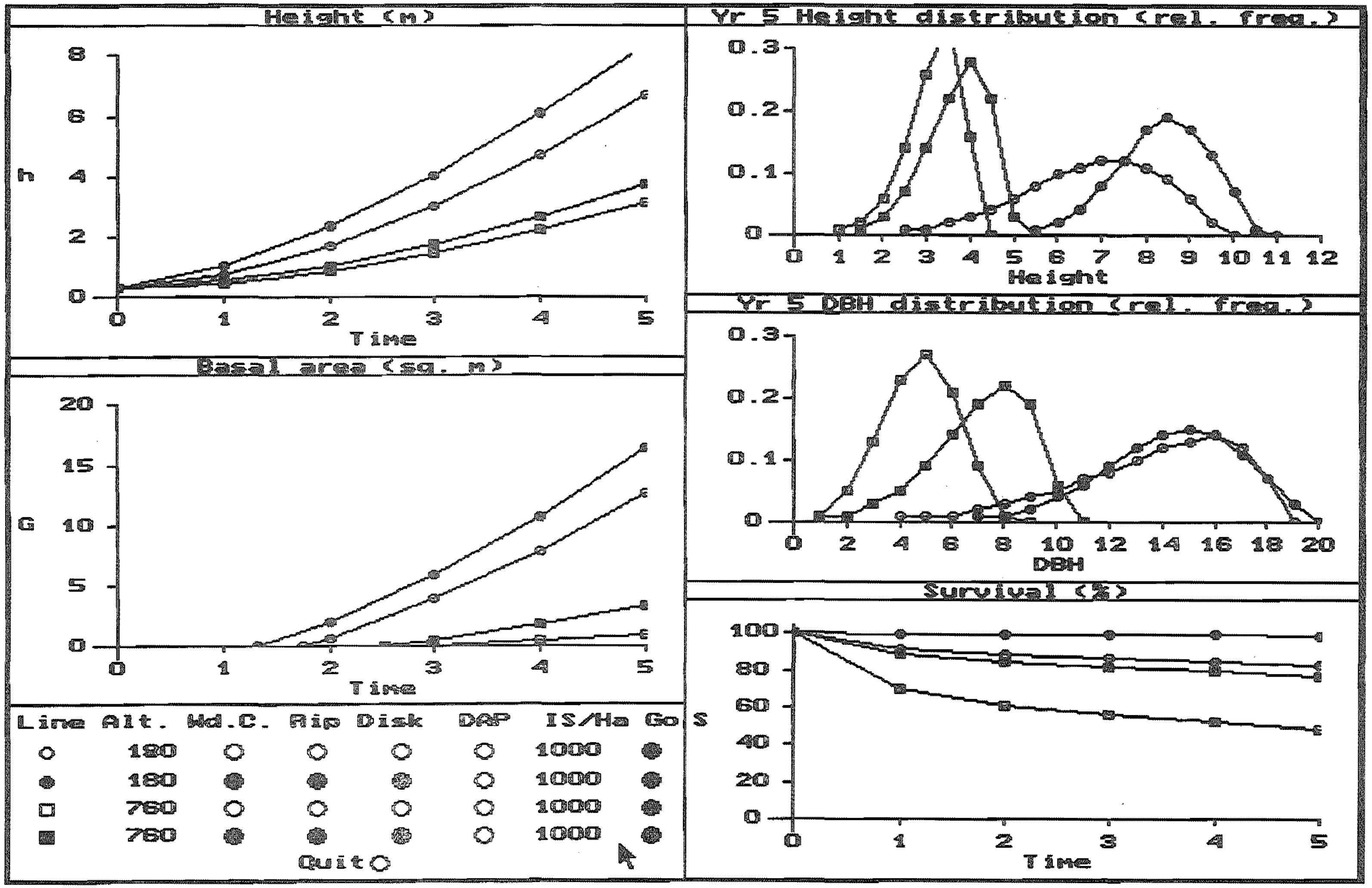

Figure V.12 - Sample screen from the initial growth model. Users nominate treatments using the control panel on the lower left. Any individual graph can be expanded to full screen size by clicking the title bar with the mouse.

prediction was poorer than that of height, because of fewer data being available.

In compartment 542, the survival model underpredicted survivals. This might be expected, given the biased distribution of model residuals.

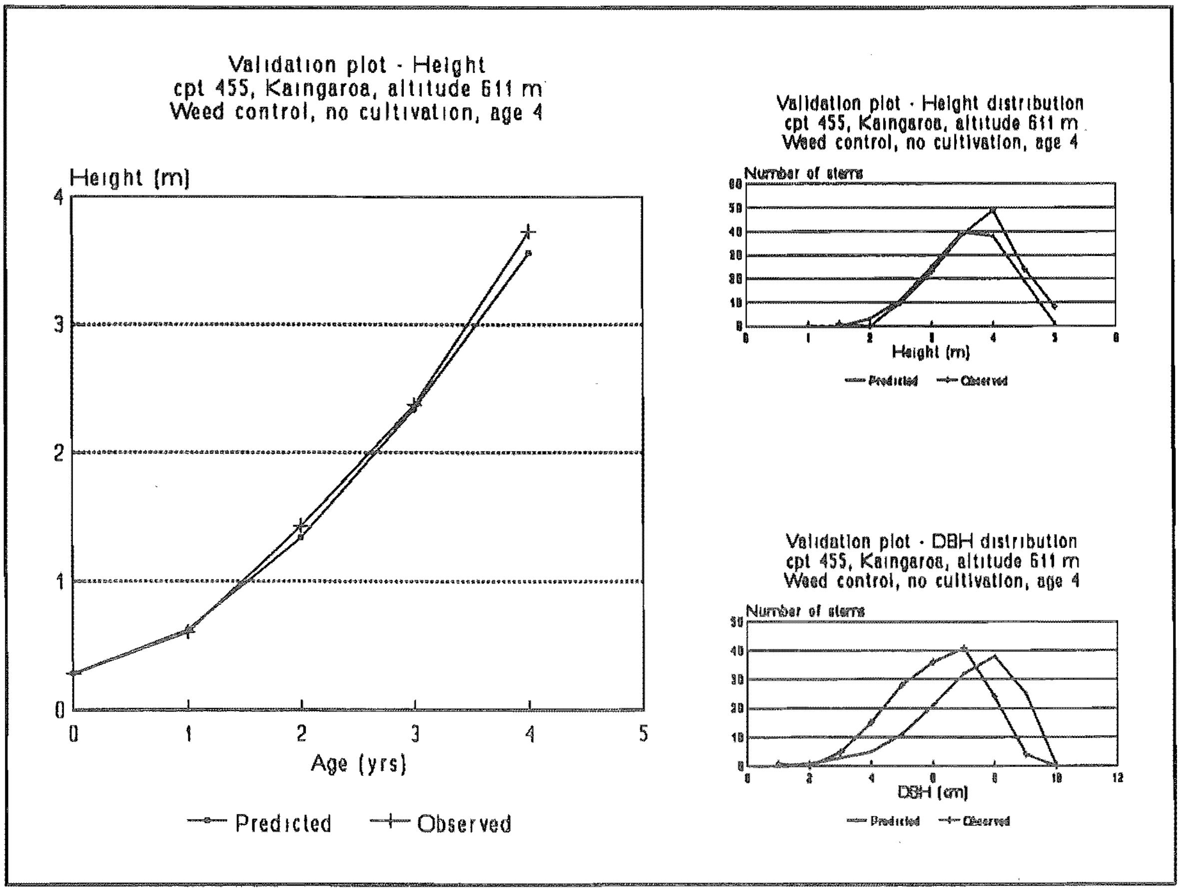

Figure V.13 - Validation plots from compartment 455, Kaingaroa Forest.

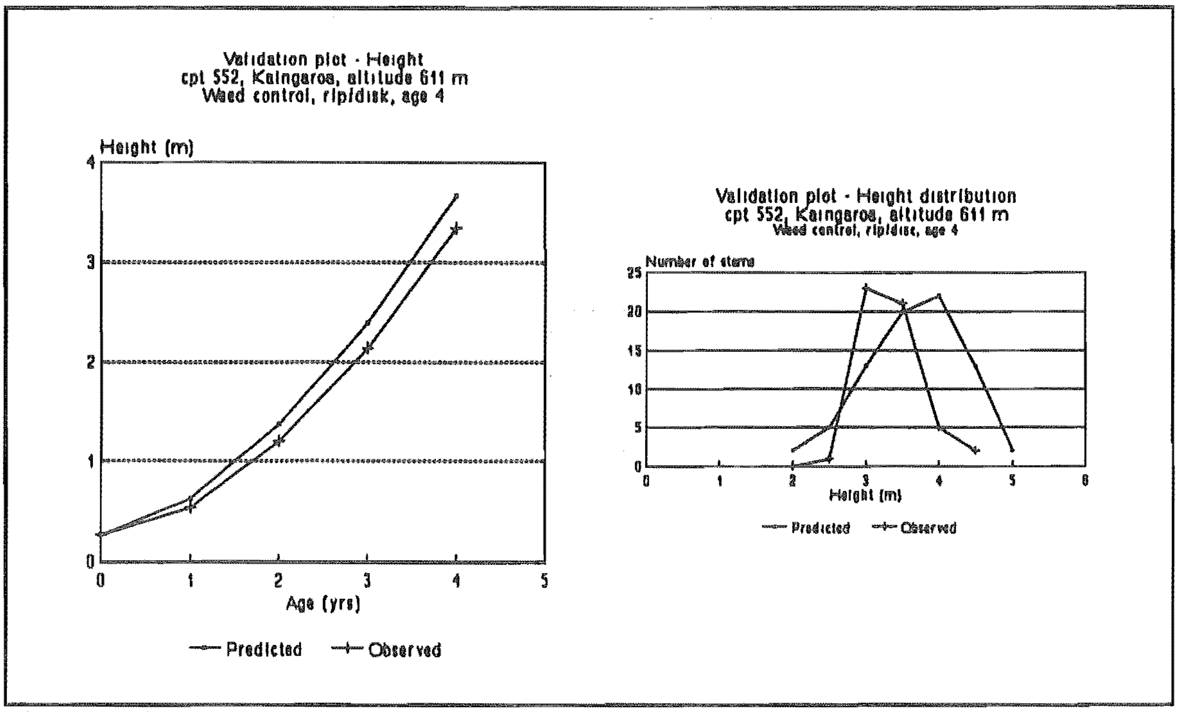

Figure V.14 - Validation plots from compartment 552, Kaingaroa Forest.

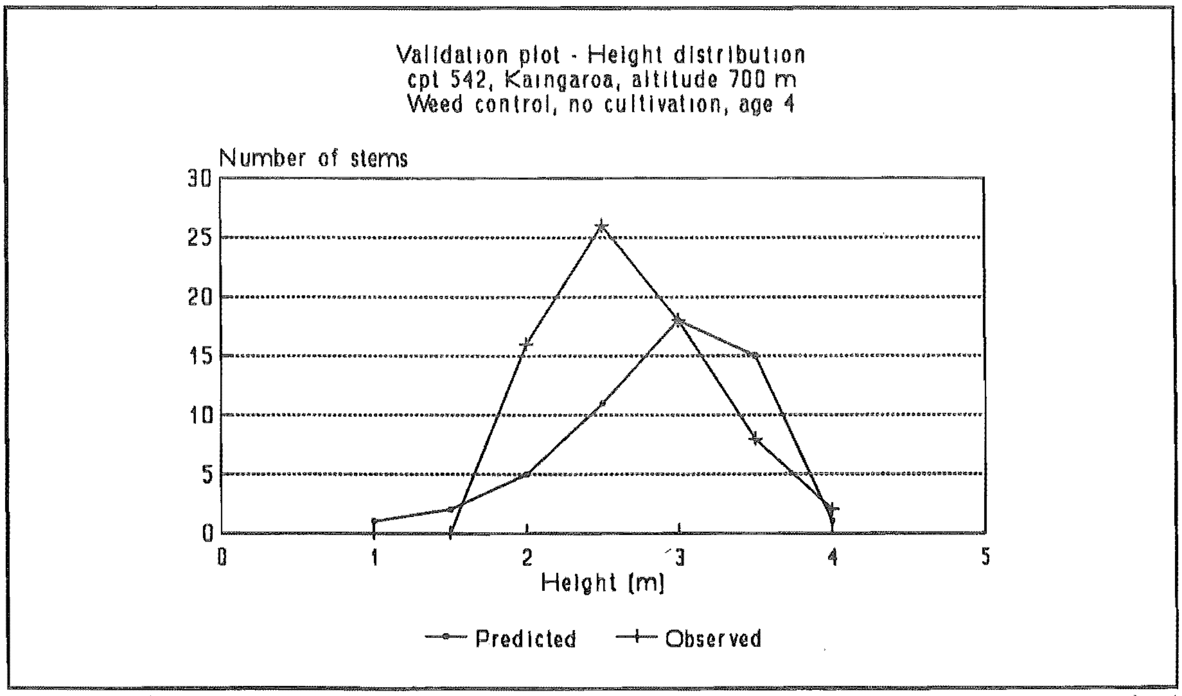

Figure V.15 - Validation plot from compartment 542, Kaingaroa Forest. The survival function underestimated survival, leading to less area under the predicted distribution than under the observed one.

V.3. DISCUSSION OF INITIAL GROWTH MODEL

1) Analysis of individual experiments

The treatments which should be included in a model of initial tree growth on pumice soils in the Central North Island were shown clearly by the analysis of individual experiments. Weed control appeared to improve survival and growth; cultivation appeared to improve survival of trees after planting; mounding appeared to improve growth; and fertilisation with phosphate and/or nitrogen did not appear to have any consistent effects. With appropriate soil analyses, it may have been possible to explain further the variation in responses to fertilisation.

More interactions were expected, especially between cultivation and weed control. With the exception of R1835/2, it must be concluded that the effects of cultivation on these Central North Island sites were due to effects other than physical control of weeds.

Only some of the experiments were designed in ways which allowed conventional hypothesis testing of effects of site preparation; identification of trends in plot residuals of models against all recorded site preparation treatments, therefore, was the main discriminating criterion for goodness of fit.

2) A model of initial growth for the Central North Island

a) Survival. The best-fitting model, as might be expected (see chapter III), was an anamorphic form, because the likelihood of mortality for individual trees was independent of stocking.

It was also expected that the best fit would be that derived from a Weibull probability density function, with the likelihood of mortality diminishing as tree size increased. Factors contributing to mortality probably varied from year to year, however, and this resulted in the difficulties experienced with eliminating bias from survival models estimated with such a small data set.

Greater mortality observed on high altitude sites and in the presence of weeds could be attributed to more severe conditions experienced by trees, and the greater length of time they were subjected to the severe conditions, due to their slower growth rates. Experiments located on frost-prone sites were planted towards the end of the planting season, and it should be noted that planting earlier in the season on such sites would probably result in mortality greater than that predicted by the model.

Improved survival due to cultivation is less easy to explain. It is possible that cultivation resulted in more consistently good planting, or that cultivation facilitated root growth and improved access to water and nutrients.

Factors contributing to the likelihood of mortality for individual trees probably included:

(i) genotype;

(ii) physiological and morphological condition caused by nursery treatment, some of which factors have been identified, especially spacing within nursery beds and conditioning regime (Menzies 1986);

(iii) handling during outplanting, the roughness of handling and the quality of planting are known to affect early growth and survival (Trewin & Cullen 1985);

(iv) specific conditions prevailing in the microsite surrounding the tree.

At a stand level, all these factors could have been included in the model if appropriate data had been recorded. Only factor (iv) was identifiable in the available data.

Factor (ii) might have been expected to have an influence on tree size at planting, and factors (iii) and (iv) would probably have affected tree size at subsequent re-measurements. Factor (iv) is also likely to have greater influence on smaller trees. It is therefore possible that an individual tree approach to modelling survival would yield an improved representation even with existing data, employing individual tree size as an independent variable.

Researchers have often found polymorphic models of survival to be superior to anamorphic ones after trees begin to compete. It is useful, therefore, to regard mortality in the few years following planting separately from in later years after tree competition has set in. Mortality due to senescence might be a third process, more likely represented by an anamorphic function.

An alternative view might be that all mortality results from a breakdown in tree physiology, and that even after canopy closure some mortality is due to stress applied by competing vegetation when weeds are present. This view ignores the fact that rates of physiological breakdown for the three different processes change quite differently with respect to average tree size and have differing explanatory factors. Mortality decreases with average individual tree size prior to between-tree competition, increases with overall crop size in competing stands, and may be independent of tree or crop size in the case of death due to physiological aging, although this latter assertion is unproven.

b) Height. The exponential function used effectively represented the increase in height growth with increasing average tree size prior to the onset of between-tree competition. The fit within individual plots was particularly good. Larger residuals produced by the model representing site preparation and site variation were due mostly to unexplained variation in site quality rather than any lack of fit of the basic function.

Other researchers have found that weed competition primarily affected diameter growth of young trees unless the trees were overtopped by the weeds, in which case height was depressed (Lanner 1985, Zutter *et al.* 1986, Richardson 1991). It was therefore surprising that weed control was found to have a strong influence on height and height variation. Part of the explanation for this may be that weed cover decreases soil temperature and increases susceptibility to frost damage in the Central North Island (Washbourne 1978, Menzies & Chavasse 1982). In experiments elsewhere, the primary effects of weeds may have been to limit the availability of water, nutrients, and light to tree crops. Some of the largest effects of weeds were found at low altitudes, however, and it is possible that the trees were overtopped in some of the plots containing weeds.

Whilst the height growth model predicts growth reliably in weed-free situations, there is clearly a need for a model sensitive to different weed species and levels of weed infestation. Data appropriate to such a refinement are currently being collected (B. Richardson pers. comm.).

Weed species and site occupancies are likely to change as growing trees occupy sites more fully, and parameters of any model sensitive to different weed species and levels of infestation will have to be in difference form, with level of competition at some point during the growth period as an independent variable. It was therefore interesting to note that the estimated parameters of the height model in difference form were virtually identical to those estimated in yield form.

Reasons for the effect of mounding on height growth are subjects for conjecture. Washbourne (1978) suggested that a raised planting position might keep trees above the coldest air, which is commonly closest to ground level. Growth of loblolly pine in north eastern Florida was related to bed height (Outcault 1984), however, the effects of bedding in Florida were probably due to improved drainage, as reported for slash pine on sites in Louisiana (Haywood, 1983), and not to frost amelioration.

As mounding often results in a temporary destruction of weed cover, and the effects on growth may be partially due to frost, one might expect that there should be a significant interaction between cultivation and weed control. Such an interaction was observed in one experiment only, however. More complete descriptions of sites, and a database which included a greater range of site conditions might have allowed the estimation of an interactive term for the model.

Possible reasons for the effect of altitude on growth are complex, and these are discussed in section V.3.2.d.

Site flatness was an important factor on some sites, with reduced growth on flat sites compared to sloping sites. Examples of large growth differences between trees on flat frost-prone sites and those on adjacent slopes in Kaingaroa Forest are known from personal experience. The reduction in growth was probably caused by frost. Limitations of the database did not allow the inclusion of flatness within the modelling framework, however. It should be noted that "less than a 3 degree slope" may not be a sufficient definition of frost prone sites, as the tops of hills may fit this description but be less frost-prone than depressions where cold air collects.

Initial stocking was found to have a detectable effect on height growth, but not nearly so marked as that observed in some of the Nelder design experiments (Chapter IV). There was no evidence of an interaction between initial stocking and weed control, and the overall effect was so small it was not worth including in the model.

Comparisons of predicted and actual height growth in the plots used for validation showed an encouraging level of agreement, but a more thorough validation is obviously required. Survival, height, and dbhob data from temporary plots at a range of altitudes and with a variety of site preparation treatments would provide a check on model predictions.

Traditionally, tree height growth has been regarded as independent of stand density by forest growth modellers (Husch *et al.* 1972), and it might be postulated that the exponential height model estimated for young crops prior to crown closure represents the same process as, and should interface smoothly with, height models of older crops. Ideally, at the age where the transition is made from one model to another, the two models should have the same derivative. It would also be desirable that the two models should predict the same growth within any age range where they overlap. However, as discussed in Chapter II, growth modelling in stands with actively competing trees differs markedly from that in young stands prior to crown closure, and it is likely that the models would predict similar, but different growth rates at equivalent ages. This would result in a modelling system which is not path-invariant if either of the models could be used between any two different ages.

Further complications which arise from using existing site index equations to predict the long-term effects of cultural practices have been discussed in Chapters II and III, and suggest that the results of such predictions could be misleading. In the initial growth model for Central North Island region described here, it is likely that the effects of weed control might diminish after crown closure.

It is recommended that, until models sensitive to cultural practices and including crops both prior to and after the onset of competition are developed, the change from the initial model to models of growth at older ages should be made at a fixed age within a decision-support system, at a time when the derivatives of the two models are as close as possible, and that the assumptions implied by the use of other models to compare effects of alternative cultural treatments at older ages (see Chapter III) should be made clear to users of the system.

c) Diameter at breast height. Far fewer dbhob than height data were available. The models estimated from dbhob measurements are consequently less precise than those estimated from height measurements. However, the adapted functional form successfully represented initial basal area growth in a form compatible with the height function.

It should be noted that when mean height is 1.40 m, basal area would be non-zero due to variation in the sizes of trees, and the fact that dbhob is undefined at heights less than 1.40 m. As time passed, the frequency of trees passing 1.40 m in height would follow a near-normal distribution with respect to time, and while a proportion of trees remained below 1.40 m, the diameter distribution would appear as an upper slice of a near-normal distribution. While this phenomenon could be represented by a model if adequate measurements were available, it is unlikely to be useful enough to be worth the effort. In a sense, the representation adopted in the models described here implies negative dbhob for trees with heights less than 1.40 m, with negative basal area values as well. The use of the "k" term as defined by the time when height = 1.40 m improved the fit of the basal area and maximum dbhob functions in the years immediately after the entire stand had passed 1.40 m in height.

Initial stocking was used as an independent variable, effectively interactive with all other independent variables. As percentage mortality was unrelated to initial stocking, and the likelihood of mortality diminished smoothly with time, the parameter estimates obtained for the basal area model incorporated the effects of greater mortality on some sites and with some treatments.

Basal area/ha growth was differently affected by weeds than by altitude, for equivalent mean heights (Figure V.16). This was further evidence that representing site quality with only height may be misleading.

If more than a tiny proportion of the trees were less than 1.40 m in height, the dbhob distribution parameters could not be accurately recovered by the methods advocated here, nor could the actual distribution be accurately represented by a Weibull function. In fact, no measurements of dbhob were available from stands where the height distribution included many trees below 1.40 m in height, and estimates of the diameter distribution have been confined to ages 4 and 5 within the model program.

It is likely that estimation of dbhob variance through a multi-linear function was possible only because of the limited age range in which measurements were collected and because of the limited dbhob database. With a greater range of ages and more data, a function which was non-linear with respect to time might be expected to provide a better fit.

Users of the initial growth model should regard predictions of basal area as being less accurate than those of height, as was evident from the limited validation conducted.

Using other basal area models to extend a comparison between cultural treatments past age 5 are subject not only to the same implications and limitations discussed for the extension of the height model with site index functions, but also to other limitations. The initial basal

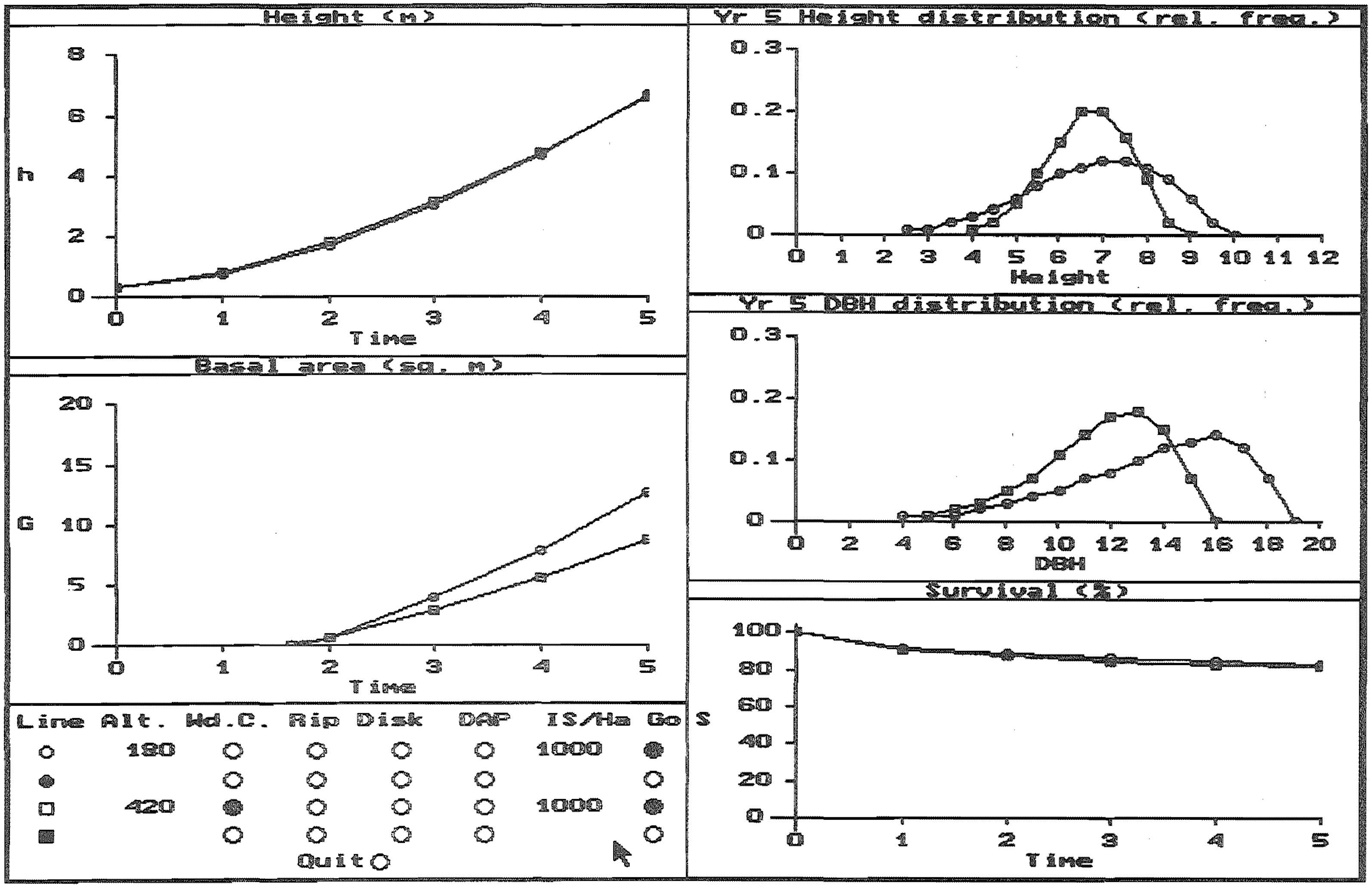

Figure V.16 - The effect of altitude on tree height/diameter ratio was different from the effect of weed control on height/diameter ratio, for stands of equivalent mean height and initial stocking.

area model uses initial stocking as an independent variable, while regional basal area projection functions sometimes imply that basal area growth at any given basal area is independent of stocking. This latter implication may be justified after canopy closure, but it would be difficult to find an age at which the initial model agreed with regional models over a range of stockings in estimates of basal area growth. In addition, basal area projection functions may or may not reflect site variation with any sensitivity. The Early growth model provides three "site qualities" for basal area projection, the choice of which to use being left to managers (West *et al.* 1982). There are currently no basal area projection functions for older ages in the Central North Island which use cultural treatments as independent variables. The implications of incorporating the initial basal area model into a rotation-length decision-support system containing other models will vary with the features of the other models, but these should be made clear to users. If a link between the initial modelling system and program EARLY is desired, the selection of the age of transfer and the appropriate basal area track in EARLY should be made within the system, with carefully considered rules probably represented through knowledge-based programming, and not left to users.

d) <u>The effects of increasing altitude on growth</u>. Survival and growth were found to be strongly correlated with altitude. Altitude is likely to be a key variable in the development of more sensitive growth models, as it is readily available to managers from maps and geographic information systems, and because several important growth-promoting factors tend to be related to it.

Norton (1985) found that monthly and seasonal minimum, maximum and mean temperatures in New Zealand could be predicted with a high degree of precision from altitude, distance of the site from the sea, and latitude. For the analysis reported here, latitude varied only slightly within the database, and distance from the sea was correlated with altitude. The reduction of temperature with altitude is mostly due to a reduction in atmospheric pressure with height. As a parcel of air rises it expands with decreasing pressure, and the energy required for this expansion is extracted from the air if there is no heat exchange with the environment (Jones 1983).

Reductions in growth with increasing altitude are likely to be partially due to decreasing temperatures with altitude. Temperature dependence is greater for physiological processes involving activation energies for chemical reactions, since higher proportions of molecules are likely to exceed any given activation energy as temperature increases. The rates of simple chemical reactions increase exponentially with temperature, but most biological reactions have a maximum rate at an optimum temperature, and decrease as temperature increases beyond the optimum. Reasons for this include changing limiting reactions as temperature increases (with differing responses to changing temperature), differing responses to temperature of opposing reactions within a process, and, most importantly, a breakdown in enzyme catalysis as enzymes are denatured at high temperatures. Processes which integrate many individual components of plant physiology often vary approximately linearly with temperature over a wide range of temperatures (Jones 1983). This may partially explain why the relationship between model parameters and altitude was found to be linear between 180 and 760 m.

Another possible explanation for the decrease in growth with altitude is that exposure to wind is likely to be greater at higher altitudes. However, as summarised in Grace (1977), analyses of wind measurements suggest that the subject is much more complex. There is often more wind, for any given altitude, closer to coastal regions, topographic influences such as vortexes and Foehn wind systems. In addition there is a lack of precision in defining the term "exposure". Analysis of toppling within experiments showed an increase with altitude, suggesting that damaging winds were more frequent at higher altitudes (see chapter VI).

Studies and reviews by Grace (1977) suggest that relative growth rates of plants increase with wind speed to an optimum, and then decline as wind strength increases beyond the optimum. Observed optima varied with species, but were generally less than 1 m/sec. Reasons for reductions in growth when plants are subjected to strong winds have not been well defined. A strong contender for a causal mechanism is the impairment of plant water status due to increased evaporation of water from leaves. However, the effect of wind on leaf surface temperature and mechanical damage are also possibilities (Grace 1977).

Decreasing partial pressures of carbon dioxide and water with altitude are further possible explanations for the observed reduction in growth with increasing altitude. Atmospheric pressure at 1000 m is 89% of that encountered at sea level (Grace 1977). Controlled environment studies suggest that carbon dioxide concentration can limit photosynthesis (Moss *et al.* 1961), although the effects vary with light intensity, and to a lesser extent with temperature and soil moisture. Release of carbon dioxide from pipes in field crops of cotton resulted in a 26% increase in yield (Harper *et al.* 1973).

The analysis of toppling data described in the next Chapter provided further evidence that exposure might be related to altitude, and identified some of the factors influencing stem straightness - a feature of crops which can be as important as growth rate in determining net returns on forestry investments.

CHAPTER VI

TOPPLING FREQUENCY

The value of modifying sites arises from more than simply the improved survival and growth examined in Chapters IV and V; increases in the number of trees suitable for selection as crop trees can also be important. One of the major influences on stem suitability is toppling, which results in stem sinuosity (Mason 1985). Toppling frequency was recorded in 17 of the 131 documented experiments. Toppling was defined as the acquisition of a lean in the standing tree equal to or greater than 15° from vertical.

VI.1. METHODS

Observations of the frequency of toppling within the first 5 years were available for 17 experiments (Table VI.1). The proportions toppled in each treatment within each experiment were transformed (arcsine square root). The altitudes, latitudes, and treatments were added to each observation, resulting in 76 records. The transformed toppling proportion was then graphed against altitude, with markers indicating ripping, discing, weed control, and fertilisation. Multiple regression models were fitted with the transformed proportion of toppled trees as the dependent variable, and altitude, latitude, weed control, mounding, ripping, fertilisation, and height at age 2 as independent variables.

Table VI.1 - Experiments used for the analysis of toppling frequency.

Experiment ID	Region	Treatments tested				Latitude	Altitude (m)
		Rip	Mound/ Disk	Fertil-isation	Weed Control		
S615	Otago	*	*	*	*	45.85	488
S542	Otago	*			*	45.94	488
Wn259	Cntrl North Island	*	*			39.37	951
R1846	Cntrl North Island	*	*	*	*	38.91	762
R1961	Cntrl North Island	*				38.77	640
R1816	Cntrl North Island					38.70	604
R1835/1	Cntrl North Island	*	*	*		38.67	591
R1037/2	Cntrl North Island	*	*			38.63	640
R1835/2	Cntrl Nth Isl	*	*		*	38.43	457
R1045/2	Cntrl Nth Isl	*	*			38.43	512
A730	Coromandel	*				36.93	244
A764/4	Northland	*	*			36.22	328
A912/1	Northland	*	*			36.21	31
A764/5	Northland	*	*			35.14	65
A912/3	Northland	*	*	*		34.85	34
A764/1	Northland	*	*			34.77	61
A764/2	Northland	*	*			34.55	31

VI.2. RESULTS

The mean toppling rate observed in the experiments was 25 %.

Toppling increased with altitude, weed control, and height at age 2. It decreased with latitude and the altitude*height at age 2 interaction. A model relating toppling to these variables had an $R^2 = 0.66$, and residuals distributed within ±0.3 of the predicted transformed toppling frequencies (Figure VI.1). Altitude and latitude were the most important explanatory variables, whilst height at age 2 was the least important.

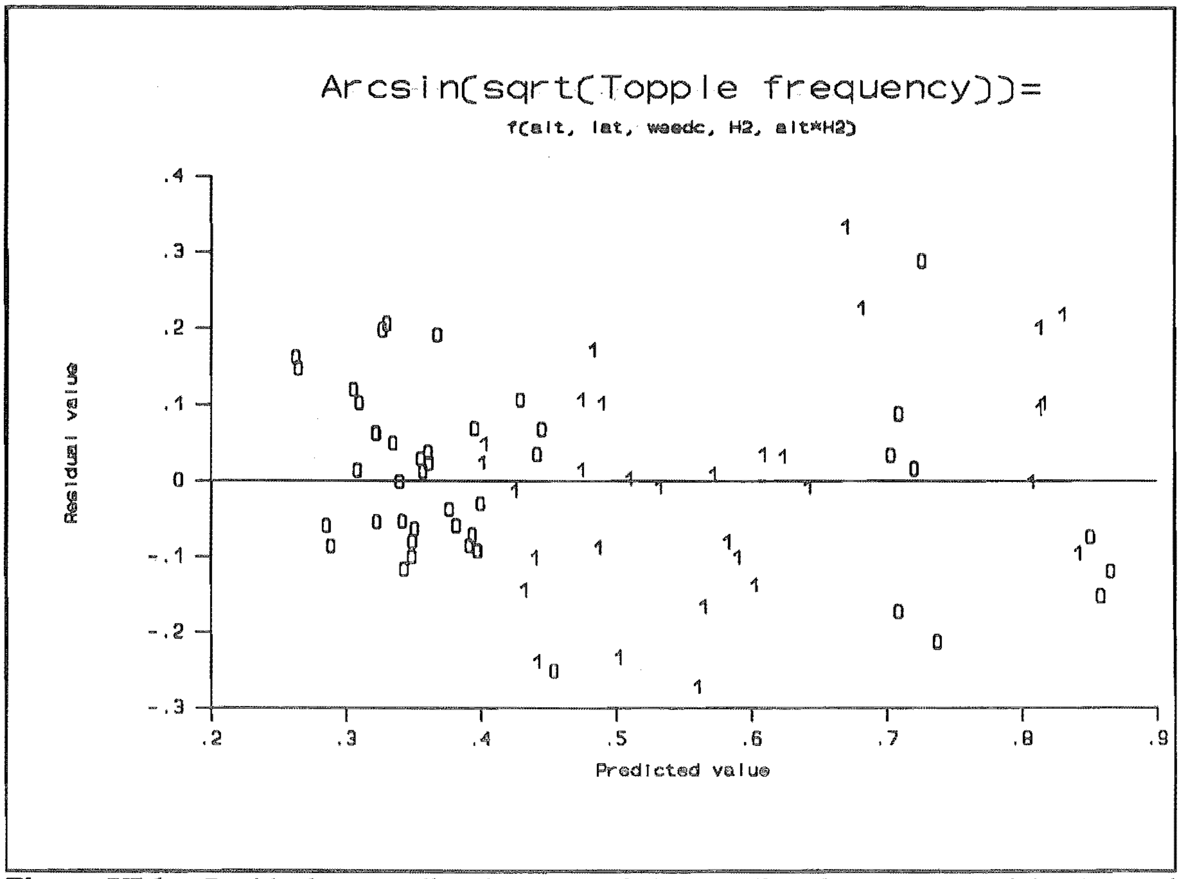

Figure VI.1 - Residual vs predicted values of the toppling frequency model. 1=weed control, 0=no weed control.

Toppling frequency was not consistently related to ripping, mounding, nitrogen fertilisation or phosphorous fertilisation.

VI.3. DISCUSSION

The results reported here provide some new indications of the factors related to toppling in New Zealand's radiata pine plantations.

1) Toppling and crop vigour

The results presented are inconsistent with an idea often expressed by practitioners of plantation establishment that toppling is always more prevalent in the presence of, and probably as a result of, rapid initial growth on highly fertile sites. Toppling frequency increased with increasing altitude and increasing latitude, variables with which initial growth is likely to be inversely correlated. However, for any given altitude, latitude, and weed control treatment, the correlation between toppling and height at age 2 would seem to indicate that larger trees might topple more frequently. Mason (1985) found that, *within* 2 year old stands larger trees toppled more frequently.

2) Toppling and exposure

Trees growing at high altitudes or with no weeds are likely to be more exposed to wind than those at low altitudes or with a weed cover, and this may explain the influences of these two factors on toppling frequency. The significance of latitude in the model is difficult to explain, and the result should be regarded guardedly in the absence of independent confirmation.

3) Amount of toppling occurring.

The mean amount of toppling observed within plots (25%) indicates how serious the problem is in New Zealand. In order to get a tentative, but probably more accurate estimate of toppling in Northland, Central North Island and Southland, the model described here could be implemented on a suitably configured geographic information system, and estimates provided which were sensitive to altitude and site preparation. It should be noted that the stock used in the experiments was of high quality, and planting was done with due care, so estimates would be based on an assumption of similar conditions in extensive plantings.

In the interim, allowing for a possible higher than average representation in the database of high altitude sites, it might reasonably be said that more than 1/5 of planted radiata pine is likely to topple to at least 15° from vertical during the juvenile growth period in New Zealand's plantations.

4) Limitations of the analysis

This model should be regarded as merely a preliminary indication of environmental factors related to toppling frequency, as the data available were limited in several respects. These limitations are discussed below.

a) Incomplete coverage. There were no data from Nelson, Westland, and Canterbury regions. The last-named region especially, may not fit the model, as strong Foehn winds are often experienced at low altitudes on the Canterbury plains.

b) Toppling frequency and crop age. The fact that particular trees had toppled was recorded in the margins of plot sheets, and the age of toppling was only sometimes indicated by an integer subscript. Perusal of the plot sheets and experience suggested that toppling was most prevalent at age two, and was relatively infrequent at ages 4 and 5, but this could not be included in the model owing to the incompleteness of the temporal recording.

5) Summary of factors related to toppling frequency

In light of this new information, a summary may be made of the factors known to be related to toppling frequency.

a) Exposure. Toppling has clearly been shown to be associated with tree sway (Mason 1985). Increases in toppling with altitude and weed control reported here were probably due to increased exposure, and are consistent with general expectations.

b) Root form. Radiata pines with distorted vertical root form have been shown to be more prone to toppling than radiata pines of equivalent size, subject to similar site conditions, and with large, straight vertical roots (Mason 1985). It is likely that this influence extends to variations in toppling frequency between stands, as was suggested by Mason (1985) as an explanation for the inconsistency of the effect of cultivation on toppling.

c) Tree size. At age 2, larger trees within stands have been observed to topple more frequently than smaller ones (Mason 1985). The results reported here suggest that this effect extends to frequencies between stands, given equivalent exposure to wind, and root form. This does not imply that managers should avoid rapid initial growth in an effort to reduce toppling, as the highest toppling rates were observed on the least fertile (high altitude) sites in the study reported here.

d) Crop age. Plantation-grown radiata pine apparently acquires a lean more readily during the juvenile growth phase than later on (Chavasse 1978, Mason & Trewin 1987).

Reasons for this are unknown, although the mechanism of root failure during toppling suggested by Mason (1985) would operate best when roots were supple, and the rigidity of older roots may reduce the likelihood of root failure during tree sway. In addition, soil surrounding the stem above the failed roots often prevents young toppled pines from reaching the ground, a mechanism which would not operate as effectively with older, heavier stems.

e) Regeneration method. Toppling of juvenile pine in New Zealand has often been observed in plantations, but no reports of juvenile instability of trees grown from seed *in situ* have been found. It might be argued that this is because few plantations are now regenerated from seed in New Zealand, but toppled juvenile trees reported in other countries were all regenerated by means of bare-root or containerised nursery systems (Clarke 1956, Gruschow 1959, Nanni 1960, Klawitter 1969, Edwards et al. 1963, Moss 1971, Eccher 1975, Bergman & Hagstrom 1976, Stone & Norberg 1978, Hulten & Jansson 1978, Huuri 1978, Tinus 1978, Van Eerden 1978, Bell 1978, Burdett 1979, Pfiefer 1982). There were reports of adjacent naturally regenerated trees being completely stable (Clarke 1956, Burdett 1979), and one researcher found naturally regenerated trees were harder to pull over with a winch than planted trees (Burdett 1979). It would appear that juvenile trees grown from seed *in situ* rarely, if ever, topple, and that transplanting trees from a nursery predisposes them to juvenile instability.

There is a need to develop bare-root regeneration techniques which ensure the development of large, straight-grained taproots soon after trees are planted. Studies within the Forest Research Institute nursery have indicated that a final undercut of seedlings 4-5 weeks prior to lifting or effective clipping of taproots after lifting might encourage development of callouses from which taproots will regenerate (Van Dorsser pers. comm.), but more radical revisions of transplanting practices may be necessary before toppling ceases to be an important problem in New Zealand's pine plantations.

Chapters IV, V and VI have developed ways of representing aspects of the establishment system numerically. Some aspects, however, require non-numerical representation. The next Chapter describes the development of a partly non-numerical representation for herbicide selection during plantation establishment.

CHAPTER VII

A DECISION-SUPPORT SYSTEM FOR HERBICIDE SELECTION

VII.1. INTRODUCTION

Decisions associated with plantation establishment should be based on both quantitative and qualitative information; quantitative information has been used to assist decision-making in a formal way for a long time, but now qualitative reasoning capability is increasingly being provided by computers. The model described in Chapter V demonstrated the potential for expressing quantitative information in a concise, useful manner. As an indication of the potential for computer representation of qualitative information, a knowledge-based system was developed to assist managers with selection of herbicides during the plantation establishment phase, to improve the cost-effectiveness of vegetation management regimes and increase users' awareness of environmental hazards.

A vegetation management (see glossary) adviser is one essential component of any forest management decision-support system, and knowledge-based programming techniques provide an excellent way to accommodate such a capability. Jeffers (1989) and Mason

(1991b) outlined the form which future computerised decision-support systems for forestry may take. User-friendly, comprehensive and malleable decision-making environments are possible, within which managers can select the types of analyses they desire. These environments may comprise geographic information systems, growth and yield models, other types of stand model, forest-level models (combinations of simulators, linear programming, and dynamic programming formulations), and other such useful tools. It is knowledge-based programming, however, which enables comprehensive integration of the tools, and which fills gaps occupied hitherto in various informal ways by handbooks, rules of thumb and/or experts.

Vegetation management components of forestry decision-support systems are best implemented in a knowledge-based structure. Design of vegetation management strategies or "regimes" involves many non-numerical analyses. Experienced managers acquire a qualitative understanding of the components of the problem: for example, susceptibility of weeds to different herbicides; times of year weeds are physiologically active; behaviour of weeds following alternative treatments; effects of different weeds on tree crops; and so on. This type of knowledge currently defies numerical analysis.

Stock (1987) proposed the following seven criteria for a suitable expert system domain, which in this context means "knowledge area represented". Designing a vegetation management regime meets these criteria.

(i) Expertise should be scarce and time consuming to learn, but the task should take only a few hours or days.

Tasman Forestry Ltd., for example, employs an expert (D. J. Geddes) in vegetation management, who acquired his knowledge from many years of field experience. Field supervisors vary in their abilities to design cost-effective vegetation management strategies, and often rely on the recommendations of a single expert within the organisation. During a test at Tasman Forestry Ltd., supervisors prescribed treatments in response to the same weed problems; their solutions varied in cost by a factor of three (Geddes pers. comm.). In some cases the treatments would have been unnecessarily expensive, whilst in others they would have had a low level of control.

(ii) The problem domain should be narrow, but deep (highly specialised), and there should be a large number of possible solutions.

Forest managers proficient in the design of vegetation management regimes are specialists with an in-depth understanding of the biology of local weed species and the effects of many treatment alternatives. Different chemicals, and/or different physical treatments are available, as set out by, for example, Preest (1985), Davenhill (1985), and Preest & Davenhill (1986) for the New Zealand scene. When these are considered over a range of weed species, environments, and seasons, the number of possibilities is large.

(iii) The problem solution should require heuristics (rules of thumb), i.e. a set of equations could not be used to arrive at a satisfactory solution.

Given the range of qualitative rules required for effective design of vegetation management regimes, it is unlikely that a set of equations would be adequate. In part this is because models of weed behaviour are almost entirely qualitative, and strategies for their control have often arisen from field experience rather than from quantitative research.

(iv) Competent experts must be available and willing to help with

development.

In the system described here, one company expert (D. J. Geddes) and one research expert (N. A. Davenhill) were much involved in pooling their knowledge and interpreting knowledge stored in data-bases.

(v) The problem should be financially important enough to warrant building the system.

Based on responses to a questionnaire which asked for areas to be treated, it was estimated that New Zealand's forest industry planned to spend approximately $7 000 000 annually on vegetation management between 1987 and 1992 (Trewin & Mason 1991). The direct costs of effective vegetation management can vary from just a few tens of dollars to several hundreds of dollars per hectare, while the opportunity costs of misapplying control techniques can be very high, either in the form of poor subsequent crop performance or as unnecessary expenditure.

(vi) Experts in the area should agree.

In New Zealand there is general agreement among experts about the broad principles of design of vegetation management regimes. Davenhill and Geddes occasionally differed in opinions but only on points of detail.

(vii) Ample data, test cases, and potential users should be available for testing the system.

Data, test cases and users were all available. Geddes (1987) had compiled a very complete vegetation management manual for Tasman Forestry Ltd., and the company's forest supervisors were keen to help with the project.

Herbicides vary in their impacts on the environment (Adams, 1988), and managers should avoid using particular products in circumstances where their use may pose a risk to adjacent crops, wildlife, fisheries or people. A computerised vegetation management adviser could accurately and quickly alert supervisors when use of a herbicide may be risky. In the system described here, warnings of potential hazards are brought to the user's attention when a herbicide is selected, and toxicity information is available at the touch of a key.

For inexperienced supervisors, a decision-support system can be used to assist with training. It is, in fact, difficult for such supervisors to cope with the wide range of substances, application rates and methods, non-chemical control methods, responses of weeds, and costs involved in vegetation management without such help. A computerised system, moreover, can make the problem more manageable, without, however, removing them from the decision process.

Commonly, when knowledge is collated within a decision-support package, important gaps in that knowledge become more apparent. It was therefore expected that the project would identify research opportunities.

VII.2. CONSTRUCTION METHODOLOGY

Construction of the system proceeded in four distinct stages: an initial prototype;

knowledge acquisition; coding; and a testing/adjustment cycle.

1) Initial prototype

A small prototype system was devised as a result of a brief meeting with Tasman Forestry Ltd. staff, based on some information contained in the firm's Weed Control manual. This was a crude program, written in BASIC, which contained knowledge of three weeds and ten herbicides. It served to illustrate the potential for a knowledge-based system, and it elicited specific suggestions for improvements.

2) Knowledge acquisition

Further knowledge about the topic was acquired from two sources: (i) the full extent of Tasman Forestry Ltd.'s weed control manual, and (ii) a series of interviews with Tasman and Forest Research Institute staff, particularly D.J. Geddes.

The weed control manual was compiled by Geddes (1987) from a range of sources, predominantly information from research conducted at the Forest Research Institute about herbicide treatments. Specific treatment information was neatly summarised in a two-way table of herbicide rates, with weeds on one axis and chemicals on the other.

Interviews were mostly conducted over a two week period. A typical interview, which would last for 3-4 hours, covered topics ranging from general overviews of the subject to specific attributes of weeds, herbicides, surfactants, and details. Each interview was taped, and later transcribed. The transcription process ensured that nothing was missed, allowed the material to be reviewed, and identified topics for future interviews. Transcripts of these interviews are on disk, in the directory labelled KA. The dates of interviews are shown in reverse order (YYMMDD), so that an ordered listing will run from earliest to latest transcripts.

3) Coding

The programming language chosen for the coding was PDC Prolog (Prolog Development Centre 1990). PDC Prolog can be implemented under several operating systems, and has many desirable attributes for knowledge-based programming. Code can be developed in a declarative way, where the rules and facts are declared and control is largely left to the compiler, or in a procedural way where information and control are both specified. In addition, the language supports both internal (in random access memory) and external (on disk) databasing, with indexing for the latter if desired. Other important features include support for lists, recursive calls in program code, and flexibility of domains for variables (so that variables can contain complex structures as values).

4) Testing & adjustments

Version 1.0 was evaluated by Forest Research Institute staff, and subsequently, after some adjustments, by Tasman Forestry Ltd. staff. There followed an iterative process of evaluations and coding adjustments.

VII.3. SYSTEM SCOPE

It was clear from the knowledge acquisition process that an ideal vegetation management decision-support system should:

(i) be capable of representing (in the form of permanent records with allowance for occasional updating by experts) many general attributes of items (weeds, herbicides, surfactants, application methods, and physical control methods) which would be fixed for any specific item;

(ii) allow temporary representation and storage of attributes for specific sites, such as weed species present, their site occupancies, their sizes, soil type, season, tree crop height, and tree crop stems per hectare, both before and after treatments;

(iii) allow for the semi-permanent representation of interactions between the items listed under (i) on a range of sites, such as predictions of weed physiological state by season, the effects of herbicides or physical control methods on weed physiological state and on tree crops;

(iv) be able to select a set of vegetation-management treatments (a regime) which best meets a manager's criteria for cost-effectiveness over the life of a tree crop by using the information in (i), (ii) and (iii);

(v) have provision for the storage of information in prose form, which may not be specifically used by the program, but which might assist managers in arriving at the best decision possible;

(vi) be user-friendly, with as much on-line help and explanation as possible, effective user interfaces, user query facilities and ability to override computer predictions, and provide hardcopy recommendations;

(vii) run on desk-top IBM-compatible computers;

(viii) have interfaces with other programs and databases relevant to forest management, such as geographic information systems and compartment records.

A system with all these attributes would have taken more time to build than was available. Plenty of specific information was available describing the effects of doses of different herbicides on weeds and crops in different physiological states, along with chemical and application costs. It was decided that the first version of the system would use this information to select herbicides for immediate treatments, while making provision for later extension to a system that would identify complete regimes involving mixtures of physical and chemical treatments for periods of several seasons.

VII.4. STRUCTURE OF THE PROGRAM

1) Overview

The system was constructed as a so-called "domain-specific shell" (Menzies 1989; Mason 1991b; Knaus & Blecker 1990). Algorithms required for herbicide selection are in compiled code, as are structures for representing different sorts of herbicides, weeds, surfactants, application methods, and their interactions. The information which makes the system specific to any given region, however, can be added to, changed or removed without further coding in Prolog.

There are two programs; one for inputting knowledge (Vegetation Management Adviser), and another for retrieval and analysis (Vegetation Management Tools). A conceptual structure is shown in Figure VII.1, the elements of which are described below.

2) User interface

The user operates the system through menus, input screens, editors, and an on-line help system which is sensitive to any specified context. The help system is extensive and complete, to the extent that a manual is not needed. Wherever possible, input is by means of menus. Input screens consist of sets of fields, usually associated with a frame, as described below.

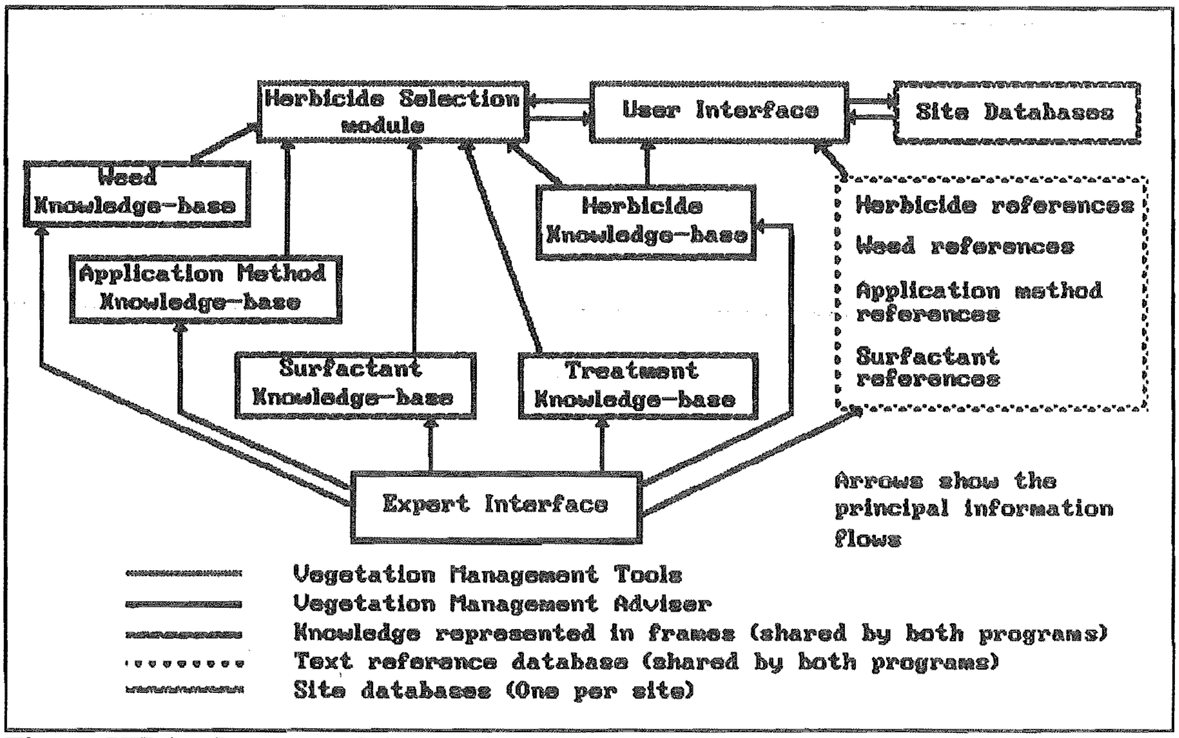

Figure VII.1 - Structure of the weed control decision-support system.

3) Knowledge-bases

Knowledge which can be updated is stored in structures which are known as frames (Minsky 1975; Jay & Knaus 1989). These are structures which contain attributes and describe behaviour associated with particular types of objects or relations. Attributes and behaviour are stored in locations called slots. For instance, the application method frame has slots for the method name, the coverage of chemical mixture per hectare or per tree, the default cost per hectare, the cost if trees are shielded (protected from the spray), whether the method can be used after planting, a device name, and several variables associated with the device if it is named. Two different types of data can fill the coverage slot, identifying whether the value is per hectare or per tree. Similarly, if an application device is named, this indicates that the application method overrides a default value for the amount of water in a mixture (defined in another frame), and the other variables associated with the device define how this should occur. All herbicide application methods can fit into this frame, and their behaviour is defined by slot values.

Frames are used to store knowledge of weeds, herbicides, surfactants, application methods, and potential herbicide treatments for three different physiological states of each weed. The slots, their descriptions, and uses may be explored by running program WCEI.EXE (available on-line at the School of Forestry, University of Canterbury), calling up a knowledge base, placing the cursor in the field of the slot of interest, and pressing F1. Some slots were included with the second version of the system in mind, and those unused in the current system are identified as such within the help system. System frames and their slots will be briefly summarised here.

a) Weed frame. Information and behaviour of each weed is represented by values in the slots described below.

(i) Weed name.

(ii) Weed type. Five types of weeds are recognised by the system: brushweeds, grasses, herbaceous broadleaves, native species scrub, and other. This slot was provided in anticipation of future developments, in which general categories of weeds will assist vegetation management regime definition.

(iii) Root regeneration defines the tendency of a weed to regenerate from roots if only above-ground plant parts are killed or severed. Index values range from 0 (no regeneration from roots) to 3 (high regeneration from roots). A value of 4 indicates a plant such as couch which has such a high root:shoot ratio that regeneration occurs from unkilled roots even after the first dose of a systemic herbicide.

(iv) Competition index is the ability of the weed to compete with crops, independent of weed size, percentage cover on the site, and spreading ability. Index values range from 1 (not very competitive) to 5 (highly competitive).

(v) Seeding ability is an index of the amount of seed produced by the weed, ranging from 1 (low) to 3 (high). It is used to define the likelihood that the weed will germinate on bare ground created on site.

(vi) Invasion ability is an additional assessment of the ability of the weed to spread that includes vegetative spread. It is used as part of the weighting of weed importance.

(vii) Spread mechanism denotes the way in which seed is dispersed on a site. Values include wind, birds, and thrown (see glossary).

(viii) Hindrance is an index of the extent to which the weed can hinder worker or machine access to the site.

(ix) Slots for seasonal physiological states are lists of possible physiological condition for the weed in each of spring, summer, autumn and winter. Physiological states are defined in terms which relate to responsiveness to herbicide rather than any strict biological process. A juvenile plant is one not long germinated that consists entirely of soft growth, and which has not been subjected to cold or drought stress. A mature flushed plant is actively growing, but in a hardened state due to age, previous drought stress, or previous cold stress. Mature dormant plants are in a slow growing or static state, and even high rates of herbicide application may not be as effective control mechanisms as low rates are for the other two states.

(x) Minimum percentage cover is the minimum site occupancy at which the system should consider the plant as relevant to development of a management strategy.

(xi) Maximum height is the estimated maximum height in metres, to which the weed will generally grow in the region.

(xii) Relative growth rate is the estimated growth rate of the weed in units of crop growth rate.

(xiii) The expected juvenile growth period is the age at which the weed will change from a juvenile to a mature flushed state in the absence of any kind of stress.

b) Herbicide frame. The behaviour and attributes of herbicides are represented by the slots described below.

(i) Herbicide name.

(ii) Units in which the herbicide is measured.

(iii) Cost per unit of herbicide.

(iv) Whether the herbicide is a contact or systemic. Contact herbicides are fast-acting, and are therefore not usually translocated to other parts of the plant and will not kill roots. Slow-acting systemic herbicides are translocated throughout plants, and will kill roots.

(v) Weeks of antigerminant action. Many herbicides prevent seeds from germinating for a period which varies from chemical to chemical.

(vi) Percentage root vs foliar absorption of the herbicide by the weeds.

(vii) Variable dose factors for light, medium, and heavy soil. Some herbicides are more active in particular soil conditions; for example Hexazinone (Velpar) is more lethal to plants growing on light soils than to those on other soil types. The dose factor will cause the system to adjust the dosage to suit soil conditions.

(viii) Warning message. This message will be displayed automatically if the herbicide is selected by the system, and users will be offered the opportunity to reject the selection.

(ix) Environmental thresholds. Eight environmental threshold values can be listed, and interpretations of these can be accessed by users of the system. Explanations of each threshold are contained within the help system of program WCEI.EXE.

c) Surfactant frame. Each surfactant frame contains slots for a name, the units of measure, and the cost per unit.

d) Application method frame. The application method frame contains slots which can represent the attributes of chemical application methods, such as aerial application and spot spraying. The slots are described below.

(i) Operation name (e.g. Spot spraying).

(ii) Coverage. The ground coverage can be represented as a percentage of total land area treated, or as an area per crop tree, but not both.

(iii) Cost of the operation, in dollars/hectare. Users will have an opportunity to adjust this to suit each circumstance, so the stored values should represent typical costs.

(iv) Pre-plant only toggle. This denotes operations which can only be implemented prior to planting of the tree crop.

(v) Shielded cost. This is the cost per hectare of conducting the operation when the crop trees are shielded from spray, if this is feasible.

(vi) Five slots are provided which specify values which the software will use to adjust the water in a mix, if water volume is governed by the device type. If these are blank, default water mix values are used, as defined in treatment frames.

e) Treatment frames. Treatment frames represent the exact mix of chemicals, surfactants and water, and the expected outcome of herbicidal treatments for specific weeds in given physiological states. The slots are listed below.

(i) Weed name (e.g. Gorse).

(ii) Weed physiological state (e.g. Mature flushed).

(iii) Treatment. This includes a herbicide name, herbicide dose, default amount of water in the mix, surfactant name, and surfactant dose. The treatment slot can also be filled by a simple operation name, although the existing treatment selection module considers only herbicidal treatments.

(iv) The percentage kill expected from the treatment.

(v) The number of weeks from the time of treatment to time of weed desiccation.

4) Text references

System references consist of simple text information, describing weeds, herbicides, surfactants, and application methods. These can be input using Vegetation Management Adviser after frames have been defined, and can be accessed by users of Vegetation Management Tools whenever they are relevant to decision-making. The references are stored in databases set up for use on a local area network of personal computers.

5) Herbicide selection module

Herbicides are selected by a module which uses a set of rules and a numerical procedure. The rule-base decides which treatments would affect the weed populations on any given site, and makes any necessary adjustments to chemical mixtures based on information contained in the frames. The effects of all treatments which fit the site, user-defined actions, the set of weeds present, and time of application are evaluated, and the results compared as described below. The system maximises weed kill multiplied by a weighting of the importance of each weed, plus the period of germination inhibition, all divided by the cost. Users can alter the treatment selection criteria by defining the relative importance of weed kill, antigerminant action, and cost.

a) Weed importance. The index of relative weed importance is calculated as a function of weed physiology, competitive ability, tendency to regenerate from roots, ability to invade sites, growth rate relative to the tree crop, a ratio of current weed height to crop height (or 0.3 if there is no crop), and a ratio of the maximum expected weed height and crop height (or 1 if there is no crop). All these values are obtained directly from weed frames, with the exception of the current weed and crop heights, which are specified by users of the system. The relative importance of these factors was determined in consultation with domain experts, and consequently reflects their opinions. Further study of the mechanisms of competition between plants would enable the incorporation of more objective weightings. Users of the system are offered the opportunity to insert their own relative weightings of weed importance as they describe their sites.

b) Herbicide selection. The herbicide selection module searches, by herbicide, for treatment frames appropriate to the weeds on a site, their physiological states, and presence or absence of a tree crop. It finds the maximum dosage, water, and surfactant required for any of the weeds present, and assesses the impact of the treatment on weed cover and physiological states. The overall effectiveness of a treatment is scored through the relation:

$$E=\frac{AG*AF+WK*KF}{CST^{\frac{CF}{50}}} \tag{VI.1}$$

where

E = index of effectiveness of the treatment.

AG = number of weeks of antigerminant action, multiplied by the sum of weed weights and the proportion of land area which is occupied by weeds;

AF = importance the user attaches to antigerminant action, expressed as a ranking from 0 to 100[6];

WK = sum, by weed, of kill % multiplied by weed weight and proportion of land area occupied by the weed, scaled up if the weed regenerates from roots and the herbicide is a systemic;

KF = importance the user attaches to weed kill, expressed as a ranking from 0 to 100[6];

CST = chemical cost;

CF = importance the user attaches to the cost, expressed as a ranking from 0 to 100[6].

The equation is derived from a simple ratio of benefits to costs, with weighting factors

[6] The rankings chosen for antigerminant action, weed kill, and cost were constrained so that sum would be 100.

which take into account the relative importance of weed kill, antigerminant action, and cost which are nominated by users. Note that a ranking of 50 for cost will cause the system to evaluate options using a simple benefit per unit cost, and that a 0 ranking of cost will result in costs being ignored by the system.

When the effects and costs of all suitable herbicide treatments have been evaluated, the mixture, costs and effects of the treatment with the highest score are presented to the user for evaluation, along with any environmental hazard warnings that may be appropriate.

VII.5. USING THE SYSTEM

1) Expert module

The expert module (Vegetation Management Adviser) is used to specify, for a given locality, the attributes of weeds, herbicides, surfactants, application methods, and their interactions. Each of these frame instances is entered on a screen with fields. Some fields have menus associated with them, some are altered simply by pressing "enter", while others ask for specific input.

Throughout the program, help can be accessed by pressing the F1 key, and menus are used for input wherever possible. The system can be driven by means of a mouse, if desired.

After frame instances have been entered, text information concerning weeds, herbicides, surfactants, and application methods can be entered in an editor. When it is relevant to decisions, this text will be accessible from the user module.

2) User module

From the first menu in Vegetation Management Tools a user can: access any text reference; access chemical toxicity information; press F1 for help; or go to a set of utilities which allow site definition and treatment selection.

To define a site, the user selects the weeds present from a menu, and is then presented with a screen containing a set of fields. Many of the field values are nominated by the system from knowledge contained in frames, but this information can be overridden if the user so chooses. Fields in which users must supply information are the percentage cover of each weed, the average height of each weed, the season, and whether each weed should be killed or saved (in some circumstances, killing of one weed can result in a worse infestation of some other, more damaging weed). If nothing is entered in the crop height field, then a pre-plant situation is assumed. After a site is defined, it can be saved to disk.

Text references relating to a weed can be accessed by placing the cursor in a field with the name of a weed, then pressing F1. It is recommended that users follow this procedure, as the text information contains helpful hints relating to the control of each weed.

To select a herbicide, the user presses F2, and the system asks what relative weights should be placed on weed kill, antigerminant action, and cost of treatment. Other questions relating to the site are posed if relevant.

After a herbicide is selected, the user may be warned of an environmental hazard. If none is indicated, or if the user elects to proceed even with the warning, the system displays the best-known herbicidal treatment, along with the predicted results, and the time for the treatment to take effect. If more information about the herbicide, surfactant, or application method is desired, the user can place the cursor in the appropriate name field, and access text references.

The user can then reject or accept the treatment. Acceptance causes an updated site screen to appear. If the treatment is rejected, the original site screen is presented, and further treatment selections will ignore the rejected treatment. If desired, a hardcopy prescription sheet can be printed.

VII.6. GAPS IN KNOWLEDGE

Construction of this system highlighted gaps in knowledge of vegetation management. For effective vegetation management regimes to be designed, accurate models of site behaviour under different types of treatments should be developed. Two of the most important areas for research are weed biology, and crop response to removal of weeds.

1) Weed biology

Provision has been made within the program for recording of weed characteristics such as relative competitive ability, reproductive ability, and weed growth rate. Studies in the central North Island and in Canterbury have been designed to measure some of these attributes (B. Richardson pers. comm.).

2) Crop response

The responses of forest crops to competition and the competitive influence of crops on weed growth on a range of different sites are important components of a site model, and their incorporation into the initial growth model is a suitable target for further research.

The responses of older crops to competition need to be quantified, so that the harvestable benefits of vegetation management can be included in decision-making.

VII.7. FUTURE PLANS FOR THE VEGETATION MANAGEMENT DECISION-SUPPORT SYSTEM

The existing system does not completely fill the criteria for a vegetation management decision-support system outlined in section VII.3., especially criteria (v) (complete regime definition), and (viii) (interface with geographic information systems, compartment records, etc.).

1) Regime selection

There is a need for a system which will include physical control methods, and which selects an optimal sequence of vegetation management treatments over several years. Two ways have been identified to achieve this. With both, an attempt would be made to minimise competition over time per unit cost of treatment.

A rule-based module, based on existing information, could simulate the treatment selection activities of a current human expert, using a backward-chaining algorithm. This alternative would involve an iterative developmental methodology, with a succession of prototypes, each evaluated by experts and then adjusted until an acceptable standard of performance was achieved. As regimes must be constructed rather than simply selected, use of a rule-base only would rapidly result in an unmanageable representation, and only a simple system would be viable. Such a module might be effective for solving problems commonly encountered, but the shallow level of abstraction involved would mean that it might be brittle (that is, it might give poor advice) when applied to unusual situations.

The second alternative would be more robust, and would include an accurate site model. Such a module would extend the existing frame-based structure of the program, and would employ model-based reasoning (Koton 1985; Fulton & Pepe 1990). This type of structure is more appropriate than simply rules for a system that is required to construct solutions (see Chapter II.2). An object-oriented version of PDC Prolog is under development (Per Bilse pers. comm.), and it is anticipated from experience to date that this would cut development time considerably.

2) Interface with other tools

The current version allows users to save site descriptions and treatment prescriptions as ASCII files. Links are planned between the system and other computer-based management tools, such as compartment record information systems, geographic information systems, and accounting systems. These are discussed more fully by Mason and Whyte (1992).

VII.7. DISCUSSION OF SYSTEM IMPLICATIONS

Computer systems are changing our culture. The arrival of the fifth (artificial intelligence) generation of computers has been likened to the change from primitive to advanced industry in the late 1880's (Winner 1984). This has brought about significant re-definition of social relationships. Many similar changes due to artificial intelligence may be foreseen (Laulan 1986). Office automation has already led to a decentralisation of management structures, and the expansion of information and service economies (Pohl 1984). Winner (1984) predicts a rise in the status of the managerial class, and a decline in that of professionals.

Many ethical questions relating to artificial intelligence applications remain to be resolved. Should people be displaced by machines (Michie 1982) and, if so, how should wealth be distributed to humans (Moshowitz 1984)? If a network of intelligent programs makes a mistake, who is responsible? How should perverse military uses of artificial intelligence be regulated? Concerns such as these have even led to a suggestion that artificial intelligence might be immoral (Le Chat 1986). Weizenbaum (1976) feels that forms of unreason are important in decision making, and that computers should not be allowed to perform some tasks, even if they are nominally capable. It is not intended that these issues should be resolved here, but managers should be aware of their existence and relevance.

Despite the unresolved ethical questions, forest managers have much to gain from knowledge-based tools. Most importantly, they can expect to have access to more comprehensive, up-to-date information, summarised and presented in a manner appropriate to any particular decision, at greater speed and with higher accuracy than ever before. This should result in more efficient use of managers, and better decisions.

The financial costs of implementing these systems are small compared to potential benefits. The system described here cost several thousand dollars to implement, but this investment might be recovered from just one significant improvement in a herbicide application on a reasonably large block of land. A change in a choice of chemical resulting from a warning of an environmental hazard might save many thousands of dollars in opportunity losses, legal fees and damages.

Development of this system has demonstrated the potential for combinations of numerical and non-numerical knowledge representation on computers to assist with decision-making during the establishment phase. Key questions addressed in the next Chapter include how the existing systems can be improved, and how the models described in Chapters V and VI might be included with knowledge-based programming to make an effective computer-based decision-support and management control system for the establishment phase.

CHAPTER VIII

GENERAL DISCUSSION

The results presented here have defined the principal types of structures which should be included in a decision framework for establishment of radiata pine plantations. Discussion of each separate study has been provided in relevant chapters, and will not be repeated here. The first portion of this chapter addresses the question of whether or not the objectives outlined in Chapter I have been met. It is also appropriate at this time to consider, given the review of establishment systems detailed in Chapter II and the current limitations of the knowledge structures defined in Chapters III-VII, what extensions are needed in order to generate an integrated computer-based decision-support system for establishment in New Zealand. Finally, this research has resulted in conclusions relating to plantation establishment decision-support; some general, and some specific to the Central North Island region. The relevance of these will be discussed.

VIII.1 THESIS OBJECTIVES

The objectives set for this project were:

(i) to assemble as many existing data as possible relating to radiata pine crop establishment in New Zealand in a form suitable for later analysis;

(ii) to develop models of radiata pine initial survival and growth which reflect a wide range of site qualities and treatments in the Central North Island region;

(iii) to build a knowledge-based system which assists managers with herbicide selection during the design of vegetation management regimes.

The objectives, it is claimed here, have all clearly been met. The aim was to define a framework for a plantation establishment decision-support and management control system. The extent to which progress has been made towards this aim will be discussed and further work required to be carried out will be identified. A complete establishment decision-support system should:

(i) adequately represent the plantation establishment system;
(ii) involve rotation-length analyses;
(iii) provide for integrated management and control.

A framework for representing the establishment system has been defined which is compatible with traditional forestry information representations, such as growth and yield models and compartment record systems, and which can be easily integrated with management and control systems.

VIII.2. REPRESENTATION OF THE ESTABLISHMENT SYSTEM

Representation of the establishment system, both in numerical and non-numerical forms, prior to thinning and pruning, is a primary requirement of decision-support.

1) Numerical models

The initial growth model for the Central North Island region includes several innovations which were required because of the unique features of tree development during this phase (see Chapter III), and provides a means of predicting the gains from a variety of site preparation treatments during the 5 years following establishment. However, extensions as set out below to the existing model would be desirable.

a) Initial growth in the Central North Island region. The most influential variable in the initial growth model was altitude. Possible reasons for this have been discussed previously (Chapter V). The correlation between altitude and site productivity reported here suggests that modellers of radiata pine growth and yield at older ages in the Central North Island might also benefit from the use of altitude as an independent variable. This has already been tried successfully for modelling Douglas fir in the South Island (Whyte *et al.* 1992), and it would appear to offer a way of making models more site-specific using values of an independent variable which managers can easily acquire.

The most growth-promoting site management activity in the central North Island was found to be weed control. Weed control, although a coarse measure of the competition actually experienced by trees, dramatically improved survival, growth and uniformity of young radiata pine. It was therefore appropriate for initial decision-support system development to be focused on vegetation management. Future work should concentrate on improved understanding of competition, better representation of the establishment system on computer, and the refinement of programs to assist with design of weed control strategies.

Cultivation consistently improved survival of young trees, and discing tended to improve growth, although not to the same extent as weed control. Reasons for these effects are unknown, but the effects cannot be ignored during decision-making. The effects of cultivation on future activities such as rates of tree planting should be more fully quantified.

Fertilisation with P and N rarely influenced survival and growth in this region, which was consistent with deficiency ratings shown in the Deficiency Atlas (Hunter *et al.* 1991). There was a suggestion that inclusion of the effects of boron deficiency in the model would be desirable in some parts of the region, and that is also consistent with information in the Deficiency Atlas. Further data would be required for this.

b) Limitations of the current initial growth model. The initial growth model described here is limited in accuracy. This is especially so with respect to basal area/ha because too few measurements of dbhob were available. Researchers should strive to measure dbhob as early as possible in their experiments, as this measurement is both easier to take and is better related to actual tree size than is RCD.

Dbhob measurements were not available above 760 m altitude. This and the nonlinearity of the relationship between height function parameters and altitude above 760 m meant that models of basal area/ha and mean height do not currently apply to sites beyond this altitude. In addition no data were available from experiments below 180 m altitude. There is clearly a need to extend the applicability of the models with respect to altitude.

The analysis suggested that site flatness should be an independent variable, with trees on flat sites at high altitudes performing poorly compared to those on slopes. More data at lower altitudes is needed before this variable can be properly included in the model.

Results of the Nelder analysis implied that height growth might be a function of initial stocking, at least when the trees are subjected to weed competition. Further investigation of this phenomenon is warranted.

West *et al.* (1982) reported that basal area/ha growth on sites which previously supported grassland agriculture was more rapid than that on sites which had been forest land. In the analysis reported here, previously agricultural sites were all at lower altitudes, with the exception of plot R1846. In the latter case, there was no evidence that this experiment was in any way more productive than other those on previously forested sites, given its altitude. None-the-less, a possible relationship between past use and productivity could be investigated if more data from high-altitude farmland sites were available.

c) <u>Stem defect</u>. Stem defect influences crop value (see Chapter II), and there is a need to represent it within the initial growth modelling system as a dependent variable. Too few defect data were available for it to be included in the study reported here.

Factors influencing the frequency of stem defect include tree genotype and toppling. The toppling model described here is limited by lack of data. Data collected by researchers should include angle of lean, age of tree, and subsequent stem deviation measurements (Mason 1985).

Toppling often occurs more frequently among the larger stems in a stand (Mason 1985), so models should represent defect across a size class distribution.

d) Other independent variables for the Central North Island model. The review in Chapter II identified several potential independent variables which could not be included in the models due to limitations of data. These included aspects of sites, tree quality, and stand layout.

The overall effect of weed competition in the model was large, with respect to both tree survival and growth. It is highly likely, however, that magnitudes of the effects vary with weed species, level of weed infestation, and crop dimensions. Given appropriate data, the initial growth model of radiata pine could be made sensitive to these factors. Such a model would be most usefully estimated in difference form, allowing for variation in weed density from year to year. If this was combined with models of weed development, a useful stand-level model of the weed/crop system would result. The understanding and some of the data required for such a model will come from experiments currently being conducted at the Forest Research Institute (B. Richardson pers. comm.).

As discussed in Chapter II, both land clearing methods and logging can dramatically affect site fertility, and both of these factors should be incorporated in the initial growth model when suitable data become available. The effects of land clearing on initial survival and growth should be clearly identified, and balanced against possible long-term losses in productivity due to organic matter loss and compaction. The latter effects probably depend on the type of land clearing employed. The value of improved site access after land clearing also needs quantification.

Although tree quality defies accurate definition, it is clear that crop performance is strongly influenced by genotype, propagation methods, damage incurred during transplanting, and planting practices (Chapter II). Including these in the model would be desirable, especially where managers are faced with clear choices, such as that of genotype. Discussions with Dr. S. Carson at the Forest Research Institute raised the possibility of assigning growth and form ratings to stock used in the existing experiments. This would involve a lengthy search of nursery records, but would significantly add to the value of the database.

Finally, the models might include effects of alternative stand layouts, if any. The question of square vs. rectangular planting spacing was re-examined by Grace (1990), and the unpublished studies referred to by Sutton (1981) should be reviewed in light of her findings. Studies have been initiated to examine the impacts of alternative stand arrangements on production, silviculture and harvesting (Terlesk & McConchie 1988). It is unlikely that effects on productivity, if any, would be significant prior to the onset of between-tree competition, but they may be sufficient at older ages to affect choices of tree spacing at planting.

One point highlighted by these analyses is the value of careful recording of *all* facts which might be remotely relevant to crop performance during the establishment of experiments, even if these factors are not being investigated at the time. If seed-lot numbers, for instance, had been recorded, it is likely that genotype would have been an independent variable in the initial growth model, and the useable database would have been larger.

e) Other regions of New Zealand. Model building was greatly simplified by restricting the data to one region of New Zealand, where soil was generally well drained, and nutrient deficiencies were few. The aim of extending the model should be to allow prediction of initial survival and growth throughout New Zealand with a single model sensitive to the effects of changes in site characteristics and management practices, if possible. This will require additional independent variables describing sites prior to treatment, as well as prediction of the much larger effects of cultivation and fertilisation which have been observed in other regions (eg: Hunter & Skinner 1986, Mason *et al.* in prep).

Latitude is likely to be important as a site descriptor, due to its correlations with temperature (Norton 1985) and insolation (Grace *et al.* 1987). Distance from the sea may also be useful, as it is also correlated with temperature (Norton 1985). It would be ideal to include temperature directly in the models, but independent variables will have to be restricted to those managers could reasonably be expected to have access to or measure.

Both chemical and physical characteristics of soils will be important independent variables when the models are extended to other regions. Estimation of nutrient deficiencies by means of the Deficiency Atlas (Hunter *et al.* 1991) might be suitable, although specific measures of deficiency such as repeated Bray P extraction (Skinner *et al.* in prep) are more likely to prove useful. The model should be sensitive to whether the fertiliser applied is slow or fast release (Hunter & Skinner 1986).

Soil texture and drainage are likely to be the most important physical characteristics when it comes to predicting the effects of cultivation on growth (Mason & Cullen 1986b).

Seasonal rainfall is limiting in some regions (Jackson *et al.* 1976), notably Canterbury, and it is expected that it will be both important in the models and accessible to managers through geographic information systems.

f) Model structure. The model structure shown in Figure III.1 was successfully employed in the studies reported here. However, as the range of site types covered by the model increases, and as more management options are included, many interactions might be expected, and the number of parameters required may make estimation difficult.

An alternative approach would be to return to the conceptual structure shown in Figure II.2, where the effects of management options on site characteristics and tree quality are predicted, and crop survival and growth are predicted from these two latter factors. Such an approach would significantly increase the depth of understanding of treatment effects, and would result in models which were more robust, since they would more accurately depict real-world relations.

2) Non-numerical representations

The vegetation management herbicide selection system has demonstrated the potential for knowledge-based programming to assist decision making during plantation establishment. As discussed in Chapter VII, there is a need to extend the representation to non-chemical control methods, and the design of vegetation management strategies lasting several seasons. A deeper knowledge representation will be required for this, and it will be achieved by extending the use of frames in the system. The decision variable will no longer be driven simply by weed kill, weed importance and cost, but will have to involve a consideration of the cost of maintaining specified levels of competition. This competition would be best assessed in terms of effects on crop performance, hence the importance of current work on relative levels of competitiveness of different weed species. As discussed in section VIII.3, a more comprehensive system would analyse benefits over rotation lengths associated with different costs of vegetation management.

Many other aspects of establishment could be partly represented in knowledge-based code (Mason 1991b). Generally, the domain selection criteria suggested by Stock (1987) should be used to determine which aspects.

It has been suggested (O. Garcia pers. comm.) that all knowledge represented in knowledge-based systems could and should be represented mathematically in terms of probabilities. The following facts, for example, could be represented in probabilistic terms:

(i) Cultivation operations on poorly drained, heavy soils in Northland should be conducted during the summer, as the region is prone to dry summers and wet winters. The likely consequences of winter cultivation are that soil will be inadequately tilled, and the operation will cost more owing to poor traction.

(ii) If mechanical clearing and burning are combined, the clearing should be done first, because mechanical clearing of charred wood is most unpleasant for machine operators, and leaves machines covered in soot.

It is unlikely, however, that measurement of the probabilities involved in these rules of thumb would be cost-effective. Nevertheless, these rules are an integral part of decision-making, and should be considered by any decision-making system, human or machine. Knowledge-based programming is an efficient way to represent heuristics such as these. In addition, knowledge-based systems are an ideal repository for diagnostic information such as that pertaining to nutrient deficiencies or pathogens, and for information on how operations should be carried out, such as herbicide application techniques.

VIII.3. ROTATION-LENGTH ANALYSES

Growth of young crops is different from that in older crops in several important respects (see Chapter III), and it is unrealistic to simply assume that differences in growth due to changes in stock or site quality recorded prior to competition will necessarily continue after crown closure.

Decision criteria such as those used in the vegetation management decision-support system and regeneration cost efficiency indices (Belli 1987, Payandeh 1987), while useful indicators in the absence of more information, do not usually indicate the true worth of alternative actions. If the aim of establishment was simply to establish an amenity, then such criteria may be appropriate. However, when one of the aims of plantation establishment is to produce wood, rotation-length analyses (Glass 1985) comparing the costs and benefits of alternatives are required, and, in the case of a forest estate, what is best for one stand may not produce the optimum outcome for the entire estate (eg: Manley & Wakelin 1990).

As an example of the effects of establishment choices over rotation lengths, choosing a selection ratio should involve knowledge of likely mortality, stem form, crop uniformity, effectiveness of crop selection during thinning, desirability of branch size control, and desired final crop stocking. The two latter factors are to some extent a function of growth rates, which may or may not be influenced by actions taken during the establishment phase. In addition, crop uniformity, while apparently much desired, has not been accurately valued. The consequences of actions which accelerate growth may be even more pronounced over a rotation length.

Growth and yield models for older-aged plantation crops currently available in New Zealand are sensitive to variation in density (see Chapter II), but lack the definition necessary to accurately depict long-term consequences of establishment decisions. However, use of these models for such purposes is inevitable in the interim before more refined models are developed. The assumptions relating to parallelism of growth trajectories outlined in Chapter III may be of some use in evaluating answers derived from them, and the sensitivity of decisions to model predictions should be carefully examined.

There is a need for long-term comparisons, in controlled experiments, of different establishment strategies. These could be used to create models incorporating the effects of these strategies throughout rotations. However, a largely empirical approach to this question would be extremely expensive and the results would not appear for decades. A more cost-effective approach would be to refine the resolution of models with respect to environmental variables and variations in density in a more process-oriented fashion. The answers to questions of long-term effects of establishment choices would appear much sooner, and long-term experiments would be used for validation.

VIII.4. MANAGEMENT AND CONTROL

Effective management involves more than simply making decisions: decisions need to be implemented, facilitated, and the operations and their effects monitored. A decision-support system should incorporate or have links to software which assists with these tasks.

1) Implementation

One of the difficulties in transferring knowledge into routine practice is a lack of familiarity with, and over-complexity of, new technology. The models described here were designed specifically for operational managers to use with little or no outside help.

The vegetation management decision-support system allows users to output a hard copy prescription for a particular site, which can be relayed directly to those who are going to implement things. In a more computerised world, this might be delivered to a work crew via electronic mail, and inserted into an optimised schedule of required operations for that crew (the crew to which the message was sent having been selected by computer, based on knowledge of the people and machinery available, and their existing commitments). At present, however, this represents a potential for the future.

2) Facilitation

There is clearly enormous potential for knowledge-based systems in the facilitation of tasks. They could be employed to provide training and instruction to inexperienced workers, and to solve problems as they arise. Examples relating to vegetation management would be specific, on-line assistance with chemical mixing, calibration of equipment, and tailoring of aerial herbicide application to site conditions as suggested by Richardson (1991).

What should be done can often not be decided without a consideration of *how* a task can be done, so the establishment decision-support system should have links to programs aimed at task facilitation.

3) Monitoring and controlling

A further potential benefit of the use of computers for helping to make operational decisions is the recording of factors leading to a decision to perform an operation on any particular site, and the comparison of projections with final outcomes. These might be projections based on mathematical models, such as the initial growth model, or projections based on qualitative models, such as a knowledge-based selection of vegetation management regimes.

Tasman Forestry Ltd., for whom the vegetation management system was devised, already has a management system in place to monitor the effectiveness of herbicide applications, based on hardcopy recordings of weed health at intervals after treatments have been applied. An extension to the computer-based system is planned which will record all treatments in, and transfer assessment information on outcomes to, a relational database. This will greatly facilitate the analysis of treatment cost-effectiveness.

Links are also planned to the company's stand record and geographic information systems, in order to further the use of information gathered. For example, the geographical distribution of particular weed species could be identified after a sufficient number of vegetation management decisions had been made through the support system, as all site descriptions would be linked to geographical locations. Such links will not only facilitate monitoring and controlling of operations, but will increase the level of integration in the company's information system.

VIII.5. PUTTING THE SYSTEM TOGETHER

The studies reported here have provided a foundation for the development of a sophisticated management tool. The immediate developmental possibilities have been listed by Mason & Whyte (1992). Further development could result in an integrated computerised system containing numerical and non-numerical representations of the plantation establishment system described in Chapter II, plus aspects of plantation management beyond the establishment phase relevant to establishment decision-making. Models of older crops have already been discussed, but non-numerical representations of information about management of older crops may also be relevant. For example, considerations of access for silvicultural operations or harvesting may have important impacts on the relative values of alternative establishment regimes.

The controlling code of this system would be knowledge-based, and there would be active links with other management tools such as stand records, geographic information, and accounting systems. This code would have to have a facility for meta-decisions (ie: decisions about decision-making, such as the best approaches to problems, when to generalise, sensitivity analyses), implemented in a way which guides and teaches users at levels matching users' capabilities.

The system would provide more of the benefits of the study reported here:

(i) more rapid, well-informed decision-making;

(ii) faster implementation of new research findings;

(iii) clarification of the important elements of decision processes, and identification of needed research;

(iv) more permanent, available, relevant and subtle representations of knowledge and expertise;

CHAPTER IX

SUMMARY AND CONCLUSIONS

This study has provided a framework within which non-numerical as well as numerical information relating to responses of plantations of radiata pine to cultural treatments at time of establishment can be usefully employed by forest managers to establish their crops - some capability to differentiate sites is catered for. Conclusions have been drawn from three separate, but related, investigations; (i) the analysis of Nelder-type initial spacing experiments; (ii) a growth model for radiata pine from ages 0 to 5; and (iii) a knowledge-based decision-support system for selecting herbicides appropriate to managers' needs.

Analysis of Nelder spacing data has revealed the following results.

1. Mean diameter growth of individual radiata pine at nominal spacings between 400 and 12 000 stems/ha was found to be independent of stocking up to age 4. After age 4, the effects of competition were evident on fertile sites.

2. A correlation between mean height and initial stocking at age 4 was clearly established in the two largest experiments, but was less clear in smaller trials.

3. Models of gross basal area/ha growth and yield showed that traditional functions,

though fitting reasonably well at ages older than 6 years, under-predicted earlier growth.

4. Adjustments to traditional functions through using time to reach 1.40 m, to allow for the capacity of trees to grow when G=0, resulted in a more reliable way of accurately representing basal area growth and yield of young crops.

Analysis of data on early establishment practice in 27 experiments measured between ages 0 and 7 years showed that:

1. Mortality of 0 to 5 year-old radiata pine in the Central North Island pumice region diminished with age, a trend which was modelled with a function derived from a Weibull probability density function:

$$S_T = e^{-\alpha T^{\beta}} \tag{IX.1}$$

2. Mortality was significantly related to:

   a) altitude - mortality increased with altitude;

   b) weed control - controlling weeds resulted in lower mortality;

   c) cultivation - cultivation consistently resulted in a 10% absolute increase in survival.

3. Mean height growth of 0 to 5 year-old radiata pine in the Central North Island Pumice region was able to be effectively modelled with an exponential function:

$$\bar{h}_T=\bar{h}_0+\alpha T^{\beta} \tag{IX.2}$$

with residuals lying within ±0.1 m of predictions from models of height in each individual plot.

4. Height growth was significantly correlated with:

a) altitude - linearly between 180 and 760 m, after which growth diminished at a lower rate with increasing altitude;

b) weed control - growth was more rapid and crops were more uniform when weeds were controlled, increasing growth more at low than at high altitudes;

c) cultivation with disks - disk cultivation resulted in small increases in growth.

Residuals from a function incorporating these effects lay within ±0.8 m of the predictions.

5. a) Basal area/ha growth of 0 to 6 year-old radiata pine in the Central North Island pumice region was able to be represented with an exponential function, residuals about predictions from which lay within ±5 m^2/ha.

b) Incorporation of the time to reach a height of 1.40 m (i.e. when G=0), estimated from the height function in the form:

$$G_T = \alpha N_0 T^{\beta} - \alpha N_0 T_{G=0}{}^{\beta} \qquad \text{(IX.3)}$$

i) allowed estimates of growth capacity when G=0, to be made over a range of site quality;

ii) resulted in consistent height and basal area models, ie: G=0 until h > 1.40 m.

6. Basal area/ha growth of 0 to 5 year-old radiata pine in the Central North Island Pumice region was significantly related to:

a) initial stocking - basal area increased with initial stocking;

b) altitude - curvilinearly between 180 and 760 m, with growth diminishing at a lower rate with increasing altitude;

c) weed control - growth was more rapid where weeds were controlled, and the effect was greater at lower altitudes;

7. Height and dbhob distributions of young radiata pine crops were able to be accurately represented by a reverse Weibull probability density function, with parameters recovered from models of mean height, maximum height, height variance, basal area/ha, maximum dbhob, and dbhob variance.

8. There was no apparent relationship between early crop performance and nitrogen fertilisation. Correlations between growth and initial stocking, and between growth and site flatness were suggested by the analyses, but these trends could not be represented precisely enough by models estimated from the available data. A possible

relationship between phosphate fertilisation and basal area/ha growth should be further investigated, although it was found to be inconsistent in the analyses of individual experiments.

Use of knowledge-based programming for weed control decision support led to the findings outlined below.

1. Development of a knowledge-based programming system written in PROLOG to hold information from many sources on herbicide application clearly showed that it can be of real value for decision-making during plantation establishment.

2. Specific information on weeds, herbicides, surfactants, application methods, and treatments was best represented in frame-like structures.

3. A properly configured computer program was able to select the optimum herbicidal treatments accurately for a variety of situations.

Finally, the framework defined during these investigations could greatly assist managers in selecting treatments during the establishment phase, and has provided indications of possibly fruitful lines of future research.

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GLOSSARY

Algorithm A defined sequence of operation within a computer program.

Allometric relationships Consistency of relative ratios of the sizes of plant parts during growth.

Artificial seeds A means of obtaining many plantlets from one seed which involves replicating embryo cells in a bioreactor, stimulating the formation of new embryos from the cells, and encasing the new embryos in a man-made capsule with nutrients.

Bare-root nursery system A system designed to raise seedlings for field planting which culminates in the lifting of seedlings from nursery beds so that the trees' roots are mostly free of soil during transport to a planting site.

Basket Whorl A whorl containing a large number of branches. The stems of trees are often weak where basket whorls have been removed, and may snap.

Blanking The replacement of dead trees, usually undertaken 1 year after planting.

Bulk seed Seed of unimproved genotype.

Certainty factor A representation of the level of confidence an expert system has in an assertion, computed as a function of both the certainty nominated by interviewed experts and the certainty of users' replies to queries.

Climbing select seed Seed collected from plus trees by climbing them to obtain cones.

Conditioning A series of root prunings, soil loosenings, and severings of seedling tops designed to prepare bare-root seedlings for transplanting from a nursery to a forest.

Control pollinated seed Seed obtained from a seed orchard where the pollination of flowers is controlled so that both parents are known.

Conversion factor The ratio between round log volume and sawn timber obtained from the log during milling. Usually expressed as a percentage.

Defect core The core of knots plus occlusion scars contained in the centre of a pruned tree stem.

Domain The field of expertise addressed by an expert system or a knowledge-based computer program.

Expert system A computer program designed to emulate the decision-making of a human expert in a narrow field (domain).

Felling select seed Seed collected from plus trees by felling them just prior to the harvest of a stand.

Fibrous root system A seedling root system which results from conditioning, having a very large number of small roots, and consequently a very large surface area.

Foehn wind system Interaction between wind and mountain range causing high energy, dry winds of the leeward side of the range.

Frame A structure within a computer program designed to hold both scalar (data) and vector (algorithmic) information.

Growth and form rating A rating given to seeds which reflects their comparative growth rates and stem quality expected after they are germinated.

Hardcopy Printed output from a computer program.

Hardening off The gradual acclimatisation of sensitive plantlets or plants to environmental extremes.

Knowledge acquisition The gathering of knowledge about a domain by a knowledge-based programmer.

Knowledge-based program A computer coding which has the ability to solve problems and make decisions using qualitative information.

Knowledge induction The automatic generation of expert system rules from a table of associations or outcomes.

Mean Top height Mean height of the 100 largest diameter trees per hectare.

Mounding The raising of soil with disks or with a bulldozer blade. Trees are generally planted on the mounds.

Occlusion The growth of tissue over the stub left after a branch is pruned.

Open pollinated seed orchard seed Seed obtained from a seed orchard where the male parent is not known.

Plus tree Tree of superior phenotype.

Ramicorn A steeply angles branch which competes with the leader of a tree.

Ripping Pulling a steel tine through the ground to shatter compacted soil. Most ripping in New Zealand is done to a nominal depth of 60 cm.

Seedling quality The potential of seedlings to survive and grow after planting.

Selection ratio The ratio between number of trees planted to the number of trees retained in a final crop of trees.

Shell (of expert system) An expert system from which specific domain information has been removed, allowing use of the inference engine for any suitable domain, once the domain-specific information has been entered.

Sigmoid S-shaped functional form often used to describe growth.

Speed wobble Slight sinuosity of a tree stem, commonly found in stands growing on fertile sites.

Stand density The extent to which a crop occupies a site.

Surfactant A wetting agent added to a herbicide and water mixture in order to increase the extent to which plants absorb the mixture.

Sweep A bend in a tree stem or log.

Thrown seed Seed expelled from the parent plant with a high velocity, as a means of spreading seed over a wide area.

Topping The severing of the top portion of a seedling's foliage, to restrict seedling size, and assist with the conditioning process.

Toppling The acquisition of a lean greater than 15 degrees from vertical by a juvenile tree.

Undercutting Passing a sharp blade underneath seedlings, severing portions of their taproots, usually the first operation during conditioning.

Vegetation management Control of species and density of vegetation on a site, which can minimise competition between weeds and a tree crop, provide fodder for grazing, and add nutrients to the soil.

Vortex Narrow gap through which wind is forced, increasing wind velocity.

Wrenching Passing a blunt blade underneath seedlings in a nursery bed, to stimulate fine root development, a part of the conditioning process.

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APPENDICES

Appendices are provided in the form of three MS-DOS compatible diskettes, with contents as set out below. In most cases, contents have been compressed, and can be unloaded into a directory on a hard disk by running the *.EXE files *from within the newly created directory*. For example, to obtain a working copy of the initial growth model, create a directory on your hard disk of any name you choose, type "cd <directory name>", followed by ENTER, insert modelling diskette 2 into the appropriate drive, then type "<floppy drive name identifier>cnimod", ENTER.

There are two modelling diskettes which contain SAS output listings from Nelder analyses, initial growth model analyses and toppling analyses, as well as a working copy of the initial growth model software.

A third diskette contains information relating to the development of the weed control decision-support system, and is confidential to E.G. Mason, Tasman Forestry Ltd., and the New Zealand Forest Research Institute. It is provided to examiners only. The system is available for use on computers at the School of Forestry, University of Canterbury.

Expert Systems for New Zealand's Forest Managers

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ABSTRACT

Expert systems programming is a branch of computing aimed at emulating human reasoning in narrow domains, exploiting the speed and accuracy of computers. Applications of such systems in forestry are reviewed, and opportunities for new forestry expert systems are suggested. Prototype forestry expert systems relating to weed control and fertilisation in New Zealand have been built. Commercial expert system shells are often too rigid to accommodate processing requirements of specific domains, and "domain-specific expert system shells" are proposed as a solution to this problem.

KEYWORDS: Expert systems, forest management, computing

INTRODUCTION

New Zealand forest managers have much to gain from expert systems.

Computer expert systems can give advice normally obtained from human experts. They have been defined as "domain-specific symbolic inferencing systems" (Kling, 1984), and tend to use sets of symbolic relationships and rules of inference, instead of the precise equations and rules for solving them which conventional programs often use.

Expert systems have advantages over conventional programs. They are generally easy to use, can explain their reasoning, use uncertain or incomplete information, and are easy to update, since their "knowledge basis" is to some extent separate from their "inference engines", which do the reasoning (Stock, 1987). Typically, expert systems incorporate heuristics and can define levels of confidence for answers they produce.

Expert system programmers often use declarative programming languages, such as PROLOG, which, instead of starting at the top of the program and working down, use inbuilt logic to select portions of the program which are appropriate to a task. Many easily programmable expert system "shells" are available, but unless the expert domains modelled happen to match the uses envisaged by shell designers, these may be inadequate.

Two main types of processing are used: "backward chaining", where a goal is defined, and processing is directed so as to satisfy the goal, and "forward chaining", where no specific goal is defined, and, given new input, processing is directed to reveal as many new facts as possible from knowledge built into the program.

Much existing forestry software uses symbolic reasoning to a small extent, but would not fit into the expert system category. For example, SILMOD (Williams, 1986) simulates the response of radiata pine plantations to a variety of management strategies, but a silvicultural expert is required to run the simulator and compare the results of alternative strategies. A suitably configured expert system might call on SILMOD several times, interpret the output, present a solution which satisfies the user's goals, be prepared to explain how it arrived at its solution, and possibly even learn from the experience.

Expert systems are complementary to human intelligence, but computers and brains have some important differences. Human brains contain about 100 billion neurons (Hubel, 1979), each with between 1000 and 10000 synapses (Stevens, 1979) – this is far larger and more complex than even supercomputers. In addition, brains work in analog fashion (Bootzin *et al.*, 1986), with a range of voltages instead of the simple on or off bits of digital computers. With a cycle time of 5 ms, brains are capable of hundreds of trillions of operations per second. This awesome power is used for such processes as vision, language, and motor control; processes which are only poorly copied by today's supercomputers. Human reasoning involves induction, analogies, short cuts, metaphors, and other "tricks outside the rules" (Laulan, 1986). However, at arithmetical operations, human powers are generally exceeded by a simple four-bit microprocessor (Michie, 1982; Reddy, 1988).

CONSTRUCTION OF AN EXPERT SYSTEM

The first step in expert system construction is to carefully define the domain (or subject area) which the system will address. Stock (1987) has identified several key criteria for domain selection:

(a) The expertise should be scarce, and time consuming to learn.

(b) Performance of the task by humans should take from a few hours to a few days.

(c) The domain should be narrow, but deep (highly specialised). This avoids the need for common sense.

(d) The problem solution should require heuristics.

(e) Competent experts must be available and willing to help with development.

(f) The problem should be financially important enough to warrant building the system.

(g) Experts in the area should agree.

(h) Ample data, test cases, and potential users should be available for testing the system.

After domain definition, a series of interviews and observations of experts are conducted, to determine how the problem is solved. Techniques borrowed from psychology, counselling, and interpersonal communication are employed to expedite the process (Stock, 1987).

In addition, it is vital that the abilities and needs of potential users are clearly identified.

Only when the expert process is clearly understood can the selection of appropriate hardware, computer languages, and software construction begin. The development process consists of:

(1) construction of a research prototype;

(2) field testing with both experts and potential users; and

(3) development of a commercial product (Stock, 1987).

EXAMPLES OF CURRENT FORESTRY- RELATED EXPERT SYSTEMS

Expert systems can give managers access to a range of forestry skills. Forestry is a diverse discipline, incorporating expertise from biological science, mathematics and engineering, to business acumen. Most forestry professionals are more adept at some parts of the discipline than others.

For experts, expert systems may offer a release from boredom as computers take over more routine tasks, and an increase in efficiency due to computer processing speed.

In addition, foresters will be able to take advantage of expert systems in related areas, such as knowledge management (Rauscher, 1987b), remote sensing, and legal reasoning (Rissland, 1988).

Current forestry-related systems have extremely narrow domains. What follows is a selection of what is available.

1. Establishment

TREES1 selects species for artificial regeneration (Rice *et al.*, 1989). The program is rule based and uses a forward chaining inference engine. Users describe sites, and the program outputs lists of recommended and possible species. The knowledge base was garnered from silvics texts and from discussions with professional foresters.

2. Fertilisation

A shortage of research and extension staff in the Cape Province of South Africa prompted the construction of ENID, an expert system for fertiliser prescription (Payn *et al.*, 1989). The system is written on EXSYS, a popular expert system shell. It asks users about site conditions, and can make recommendations after considering a variety of different types of information, such as soil tests, soil type, location, climate, etc. At any time, users can ask for an explanation of the reasoning which led to a prescription.

3. Pathogen Diagnosis and Impact Assessment

Diagnosis was one of the primary areas addressed by early expert systems, and the potential for diagnosis within forestry is great. A diagnostic system developed for *Pinus resinosa* incorporating 750 rules "performed as well as experts, and better than foresters" (Schmoldt, 1987).

An integrated pest impact system developed for the US Forest Service incorporates biological, social, and economic factors to predict the effects of different types and levels of pathogens (Buhyoff *et al.*, 1988).

4. Roading

A knowledge-based forest road planning system in Indiana is capable of determining the optimum road corridors on a digital terrain model. The program identifies ridge-top "nodes", and analyses the feasibility of links between the nodes. To arrive at a solution it integrates a data matrix, a rule-base, and a minimisation algorithm. Output is in graphical form. Users can challenge the system, and the system will analyse "what if" queries (Thieme *et al.*, 1987).

5. Fire Fighting

In southwest Quebec, Canada, fire controllers are responsible for immense areas of forest, and commonly encounter 300–800 fires per season. After years of experience, controllers develop the judgement required to make an appropriate response to an alert. An expert system has been developed which uses the initial fire report, a geographic information system, weather reports, and a log of available fire control resources to prescribe a response (Kourtz, 1987).

6. Modelling

PROFIT is a program capable of parameterisation of biological simulation equations (Olsen and Hansen, 1987). The numerical analysis is performed by modules written in Pascal and Fortran, and the results are passed to a symbolic processing module written in Prolog. This module analyses the curve shape, and provides feedback to the other modules. The current version of the system is monotonic, that is, once it has arrived at an interim conclusion, it won't change it's mind. A non-monotonic version is under development.

7. Harvest Planning

Implementation of linear programming solutions can be time consuming. With spatial limitations on harvesting, such as maximum clear-cut size, and minimum distances between harvested blocks, the solutions are not always feasible. Hokans (1984) used a discriminant function to model an expert's implementation of a linear programming solution. The independent variables were:

(1) proximity to roads;

(2) proximity to other harvested areas;

(3) stand condition; and

(4) stand size.

A random sample was taken from the unharvested area to form the alternate population.

The future forest condition was simulated using growth models, and the implementations of future linear programming solutions were simulated using the discriminant function "expert". In this way, the long- term consequences of different spatial solutions could be simulated and evaluated with a minimum of professional manpower.

8. Use of Geographic Information Systems

Geographic information systems are computer programs capable of integrating terrain information from a wide range of sources. Current systems, while exceptionally useful to land managers, are notoriously difficult to query, and have relatively crude output (Robinson *et al.*, 1987).

ASPENEX is an expert system interface to a geographic information system (White and Morse, 1987). Loaded onto a personal computer, it consults a geographic information system which resides on a mainframe. The rule-base models forest management expertise, and the program recommends management objectives for different tracts of land. Users of ASPENEX need not develop any expertise in operating the geographic information system.

FUTURE VISIONS AND CURRENT PROJECTS

Many expert systems provide a supporting environment for experts, undertaking boring, time consuming, and/or complex tasks. Human allocation of tasks in relation to task characteristics has been described by Gordon *et al.* (1987), and is summarised as follows:

Task Characteristics		Allocation
Difficulty	Interest	
Easy	Interesting	User allocates task to self
Hard	Interesting	User attempts to perform task in conjunction with expert system
Easy	Boring	User allocates tasks to expert system
or		
Hard	Boring	

With the advent of hand-held IBM-compatible personal computers, such as that manufactured by Paravant, foresters need only await development of the software in order to carry their personal forestry advisory assistants in their pockets. Some of the programs they will use may be described below.

1. Establishment

Nursery management is a qualitative domain, where "green thumbs" carry more weight than complex formulae, and is therefore suited to expert system applications. The important considerations are described by Menzies (1986), and may be best covered by a set of programs providing advice on different aspects coupled to a crop state database.

Species selection programs (Rice *et al.*, 1989) might be expanded to include economic factors and timber uses, as outlined by Clifton (1986).

A comprehensive tabular guide to herbicide application in New Zealand's forests has been built (Preest and

Davenhill, 1986). An expert system based on these tables could be expanded to include application procedures, with prescriptions suited to the unique weed complex on each site. The author has already built a research prototype for this purpose, which selects herbicides for a limited number of weeds and their combinations. It queries the user about the site, the timing of application, and any further information needed to arrive at a solution. At any time the user can ask why a question is being asked, and it can give a detailed explanation, in English, of its reasoning.

A variety of options are available for managers wishing to clear land or cultivate soils (Mason and Cullen, 1986). This information could be available in expert system form, along with costs of machinery. For any given ground cover type, terrain class, and soil type, the most cost effective treatment could be prescribed to suit the manager's goals.

A comprehensive soil fertilisation adviser would be a valuable aid. Fertilisation prescriptions could be made in a variety of ways, with a range of confidence levels. Soils could be identified using a set of queries relating to location, slope and visual features of the soil horizons, and the prescriptions made from established records. Alternatively, soil test data could be used, such as sequential Bray P (Skinner *et al.*, in prep). A further option would be to use the results of foliage analysis, or perhaps identification of visual nutrient deficiency symptoms (Will, 1985). Application methods and sources of nutrients (Mead, 1986) could also be included. A prototype system has been built for New Zealand conditions.

A computer expert on prescribed fire planning is under construction (Malave *et al.*, 1987). It will consider such things as fire behaviour and safety limitations, following input relating to fuel, weather, and burning objectives.

As programmers develop expert system skills, it may be possible to combine the above systems into an integrated plantation establishment adviser, capable of prescribing establishment regimes for different sites.

2. Silvicultural Regimes

CHAMPS, a computerised habitat analysis and multiple use prescription system for personal computers, will use forest information to generate silvicultural prescriptions and evaluate management goals (Rauscher, 1987a).

Similar advice has been given in the NZIF Forestry Handbook by Knowles (1986b). Expert systems could be built which help managers to use the range of models and estate planning programs already available. They would set up appropriate inputs, run several simulations on the existing models, and interpret results for a user.

As mentioned previously, a non-monotonic parameter fitting system is under development (Olsen and Hanson, 1987).

3. Agroforestry

Agroforestry involves a mixture of forestry and farming expertise (Knowles, 1986a; Tombleson, 1986), and expert systems would be a useful way of extending the capabilities of both kinds of professionals.

4. Logging

Many opportunities exist for expert systems in logging, with applications such as roading (Farley, 1986), equipment selection, optimisation of spatial planning, machine configuration and maintenance, and transport system monitoring. Most of these applications would be closely tied to digital terrain models, and could call on a wealth of existing software developed by the Forest Research Institute in Rotorua.

5. Geographic Information Systems

Applications of expert systems in geographic information systems will be in four broad areas (Robinson *et al.*, 1987):

1 Map design.

2 Geographic feature extraction (detection of ridges, valleys, etc.).

3 Geographic database systems (user friendly interfaces for queries).

4 Geographic decision support.

6. Disease and Pathogen Diagnosis

This is clearly an easy application with existing software, and requires only appropriate collaboration between programmers and experts. Some information is available in tabular form (Ray and Rawcliffe, 1986; Alma, 1986).

7. Knowledge Management

Current knowledge management systems will appear clumsy and archaic in comparison with future expert system based products. Rauscher (1987b) identified the shortcomings of current systems:

- word processors only work sequentially;
- document database;
- hypertext works well with information chunks, but does not handle links between chunks with any sophistication;

(4) logical knowledge management systems have only single-concept chunks with complex functional links between chunks.

Rauscher proposed "ideal" system specifications:

(1) multi-concept chunks;

(2) hierarchical relationships between chunks; and

(3) expert system help with queries.

With such a system in operation, he suggests that publication of scientific results would be in the form of additions to, or modifications of, the knowledge management system.

8. Comprehensive Systems

Comprehensive forest management decision tools are probably beyond the scope of existing expert system technology, but may become feasible as hardware and programming skills progress.

A red pine managers' advisory system is under construction (Rauscher and Benzie, 1987). It will be based on a red pine manager's handbook, linked with a growth model, and will produce justifiable conclusions.

White and Morse (1987) are planning intelligent "Integrated resource management automation" as a sequel to ASPENEX.

Decision support systems might include geographic information systems, growth models, roading and harvest planners, pest diagnosis, etc. It has been suggested that these systems "could be one of the most important research and development tasks that lie ahead" (Buhyoff *et al.*, 1988).

DOMAIN-SPECIFIC SHELLS

The most viable forestry expert systems in the immediate future would be in a form which might be labelled "domain-specific shell". This would be a shell which has rules and algorithms pre-programmed to suit a specific domain, but which lacks most of the details necessary for a particular local implementation of the domain.

As noted by Stock (1987), expert systems are easily updated because knowledge bases are kept largely separate from inference engines, but the two are almost never entirely separated, and hence the awkwardness of generalised expert system shells for many applications. Users of generalised shells often encounter a particular type of algorithm, reasoning, or analysis which the shell is either incapable of conducting, or which can only be done with great difficulty. This leads to inferencing dictated by software rather than by the demands of the domain.

In many instances, the type of processing required for a particular domain does not vary from say, region to region, but the details do vary. As an example, the herbicide adviser under development (named Weed Killer), is tailored to the needs of *Pinus radiata* plantation managers in the Bay of Plenty region of New Zealand. With changes to the basic prescriptions, control substances, handling, and so on, basically the same program could be used for a different crop in a different location.

A user interface could be carefully designed to enable a domain expert with no programming experience to make the changes. In a sense, the already "expert" shell would be "learning" the details of a new situation from the human expert. This would involve a kind of "meta-programming" which, at least in the case of Weed Killer, is entirely feasible.

Domain specific shells would lack many of the disadvantages of generalised shells, would reduce the amount of code duplication during expert system development for different areas of the same domain, and would probably render many otherwise marginal expert system applications economically viable.

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DISCUSSION

Crutchfield – If you take your car into the garage and have it analysed by computer system, is that an expert system?

E. Mason – Probably, yes it could be.

M. Wilcox: – A eucalypt site selection system is used in Australia. It isn't called an expert system, but it does the same job.

Danks –Is the system adaptable for updating and how much time goes into updating?

E. Mason –Yes, updating is important. The PROLOG system is a very good system for updating.

Porada–Back in the 1920s, would the system have chosen radiata pine for New Zealand?

E. Mason– Probably not.

Nicholas – How many other systems have you looked at?

E. Mason – Some systems included aspen and red pine. In the short term, local information or application is more important. Maybe in the longer term wider information should be able to be used.

Sheik Ali Abod – How does the system cope with definition of interface?

E. Mason– It is possible sometimes to arrive at contradictory conclusions.

Riley – It seems to me that very few of these systems are operating. A lot of care, reprogramming and recalibration is required and you can come up with totally erroneous answers.

E. Mason – I agree that is a danger, but it would help if facts were kept separate from rule of thumb.

Balneaves– You need to inspect sites rather than make decisions in the office. I suggest you should use both.

Nelson – I like the principle, but decisions, on the use of herbicides for instance, can be dangerous in the wrong (unqualified) hands.

Sheik Ali Abod –It depends entirely on who writes the program.

E. Mason – Yes

Establishment or Regeneration Decision Framework for Radiata Pine in New Zealand

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ABSTRACT

The establishment phase is an opportune time for managers of radiata pine plantations to prescribe cultural practices that will hasten crop maturity and offer a better chance to shorten crop rotations. In the first two or three years of their life, small seedlings do not compete with one another, and their growth is limited only by site micro-environments which are relatively easy to manipulate. There is a need to develop accurate models of crop growth and development during these early formative years to help managers decide what treatments should be applied. These models should form part of a coherently structured system portraying long-term crop development, and should include outputs that are compatible with, and appropriately sensitive for, analysis of subsequent crop growth and yield. Suggested models to predict juvenile tree survival, growth and stem form are presented by way of example. An existing database suitable for model development is shown to be available. It covers a wide range of sites and management strategies, but there are gaps identified. The inclusion of an economic analysis to the modelling framework is briefly described, and a computer expert system framework to assist managers with decision making is tentatively outlined.

KEYWORDS: Establishment, site preparation, growth modelling

INTRODUCTION

The purpose of this paper is to show how the wide base of knowledge needed to make decisions during radiata pine plantation establishment or regeneration might be summarised as a decision framework.

In response to a nationwide questionnaire on establishment research preferences, New Zealand forest managers indicated that they were most interested in accurately predicting the benefits of cultural practices, in order to make cost savings without jeopardising final-crop values. There may indeed be an opportunity to save on expenditure, since it has been estimated that the annual cost of establishment operations in New Zealand is about $13.5 million for site preparation, and $6 million for planting, not including overheads (Mason and Trewin, 1989).

The costs of operations are generally well known, but how the benefits vary between sites is often obscure. In some regions, local trials have provided insights into the benefits of site preparation, but there are many instances where no adequate trials have been conducted, and managers lack the means to predict the results of their decisions.

Use of the available pool of information in the form of models is one way to help in making effective decisions. This option is explored in some detail here, particularly with respect to the manipulation of sites before or immediately after planting.

VARIABLES DESCRIBING THE CROP

Radiata pine plantation establishment (both new and regenerated crops) can be perceived as the interaction between crop quality prior to the first tending treatments (often at age five), site factors, seedling state immediately after planting, site manipulation, nursery practice, initial stocking, and costs as shown in Figure 1. Some of the major factors shown are discussed below.

1. Stocking and Stem Form

Success of establishment is often expressed in terms of survival, but this measure on its own is inadequate. On some sites, a proportion of surviving trees are worth little due to low vigour, stem defects, or attack by pathogens. A better indicator of success would be the number of stems prior to first thinning which could qualify as potentially useful crop trees. Common stem disorders are low vigour, ramicorns, basket-whorls, foxtails, double leaders, pith eccentricity, sweep and "speed wobble". Some of these

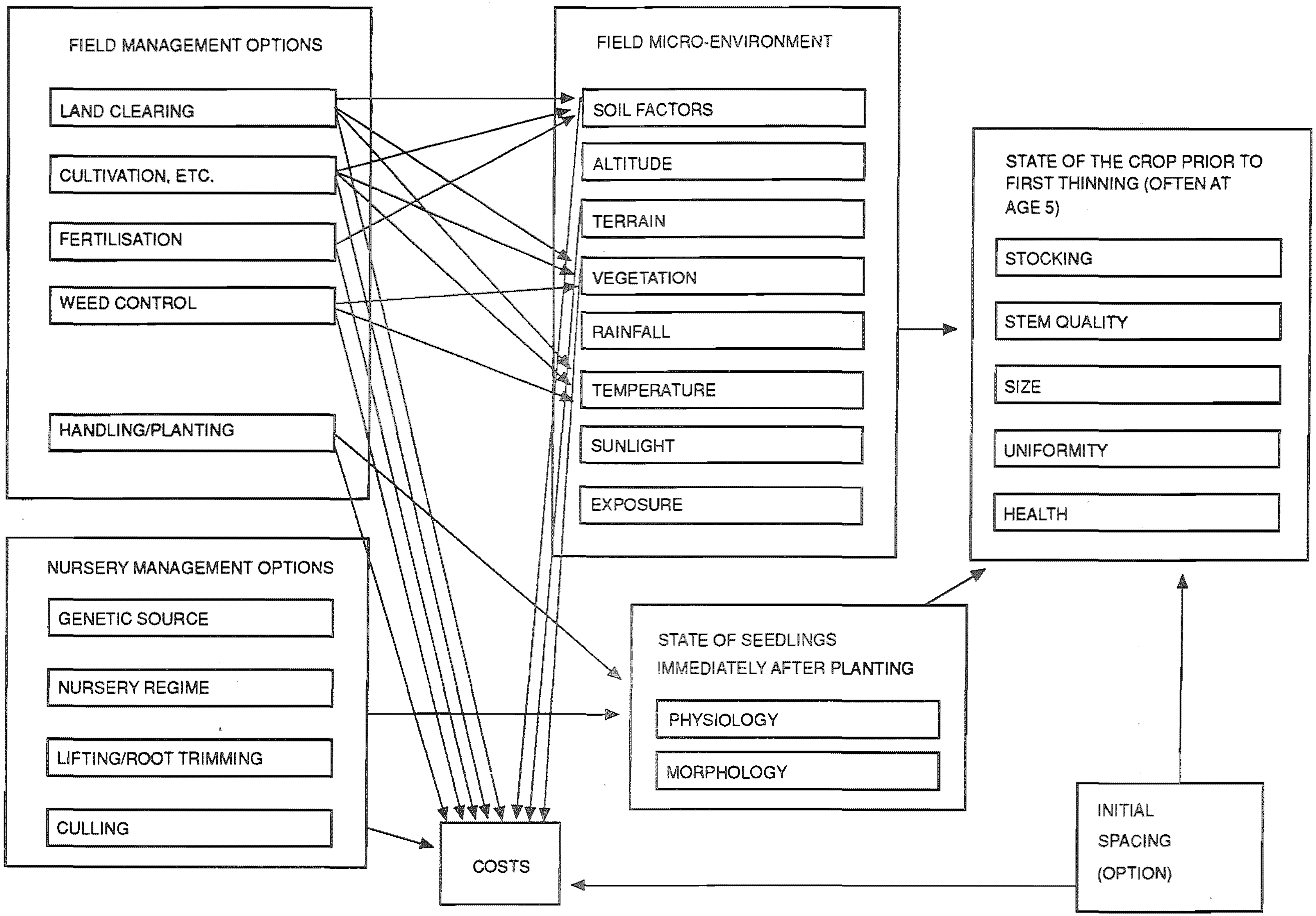

Figure 1 – Conceptual model of plantation establishment

defects are a function of genotype, but low vigour and double leaders are often induced by pathogens, nutrient deficiencies or other soil factors, while "speed wobble", pith eccentricity, and sweep are often caused by wind or snow. Any one of these defects could significantly lower the value of the crop if defective trees have to be retained in the harvestable crop.

2. Growth

Traditionally, emphasis has been placed on rate of growth in either height or diameter in absolute terms. However, crop uniformity is also important.

Growth immediately after establishment is usually expressed as diameter at the base of the stem and/or height of the stem. Diameter at the base tends to be more variable than diameter at breast height (dbh), so researchers often begin measuring DBH when all but the runt trees are tall enough.

Crop uniformity is generally expressed as a coefficient of variation in height and/or diameter (Mason and Cullen, 1986). Initial planting stocking can be close to the desired final crop stocking in uniform crops, since each tree fits the size criterion for crop trees. Uneven crops, on the other hand, are more expensive to treat silviculturally, and need at the present time between four or five seedlings to be planted for every one to be retained in the final crop. With greater lack of uniformity, crop tree selection is more difficult, and each tree may have to be pruned to a different height.

3. Correlations Between Measures

The measures of initial crop performance described above are often correlated, both within experiments on the same site, and, to a lesser extent, between sites. Rapid initial height growth is usually accompanied by rapid diameter growth, and also is often associated with low mortality and crop uniformity. Defect frequency is less well correlated with the other measures, however.

4. Use of Measures of Crop Quality at Age 5

The above measures of crop quality need to be encompassed within an economic framework. One of the keys to efficient establishment is to balance expenditure on site preparation/ stock quality with expenditure on initial stocking (Figure 2). A minimum expenditure is required on each to achieve a desired number of acceptable stems for crop selection. A manager's task should be to minimise that expenditure for any given site. In practice, most managers opt for excessive expenditure (above and to the right of the curve) in order to

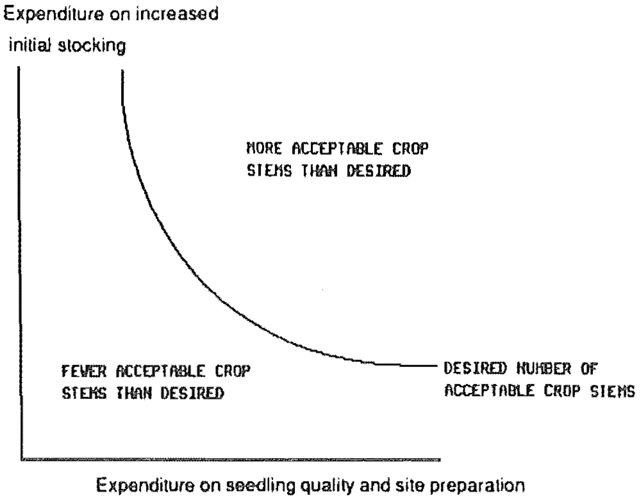

FIGURE 2 – Relationship between initial stocking, seedling quality, site preparation, and numbers of acceptable crop stems

guarantee success, because the effects of management strategies can be estimated only approximately.

Relying primarily on higher selection ratios to achieve acceptable crop quality is not ideal, however, because many effects of low-budget/tree establishment are not redeemable through thinning: for example, if tree survival is patchy, portions of the site can remain unoccupied for the entire rotation, or if planting is poor, larger trees have a greater propensity to topple (Mason, 1985), and are then unsuitable for selection. Then, if more trees are planted to allow for losses, thinning costs increase. Variable growth on poorly prepared sites generally reflects variation in site quality, and selection of larger trees during thinning is no substitute for an overall improvement in site quality brought about by site preparation. In addition, cultural practices which improve survival, crop uniformity and stem form often have the potential to improve crop yield.

Effects on final crop values of increasing initial radiata pine growth through cultural practices have not been adequately measured in New Zealand. Estimates of these effects vary depending on various assumptions:

1. The duration of the treatment. If the change were temporary (with respect to the needs of trees), and resulted in no marked change in tree form above and below ground, then one might expect that growth trajectories of the treatment and control would initially diverge, and then, when the sites were again equivalent, would assume parallel trajectories (parallel such that, for any equivalent volumes, the age difference between the two treatments is constant). In such a case, existing growth models might be used to predict final yields once the magnitudes of temporary growth increases were determined by experiment.

2. The capability of the site to support more rapid growth. To assume parallel trajectories, one would also have to assume that aspects of the site other than those altered by the treatment were capable of supporting a more rapid initial growth, and that future treatments such as thinning would not change the trees' requirements with respect to the altered growth input.
3. The effects of subsequent treatments. On some sites, a future treatment may reintroduce the change in growth inputs. For example, a thinning may increase individual tree growth to the point where nutrients are again limiting, and fertilised plots may resume more rapid growth.
4. Changes in form. Significant changes in form, such as the relative surface areas of foliage and roots, may so alter the trees responses to events such as droughts, that the trajectories would no longer be parallel.
5. Physiological age effects. If the initial treatment markedly increased initial growth, then the effects of physiological age might preclude any parallel growth between control and treated plots.

If changed cultural practices or genetic improvement resulted in lasting changes to growth inputs, then a further assumption would be required if traditional growth models were used to project the effects of cultural practices on final yield. It would have to be assumed that the growth input(s) changed by the cultural practice were equivalent to changes which occurred naturally between sites of differing quality as expressed in the models.

Apparent parallelism after an initial growth increase has been reported after weed control (Preest,1977) and after cultivation (Mason *et al.*, 1988; Wilhite and Jones,1981).

It should be noted that, if treatment growth trajectories are parallel, effects expressed in terms of multi-dimensional measurements such as basal area and volume are likely to continue to increase. Woollons *et al.* (1988) reported continuing increases in the differences in basal area between fertilised and unfertilised plots after more than a decade of measurements in four experiments, while the trajectories were apparently parallel in three out of the four cases (Woollons, pers. comm.).

Glass (1985) estimated the cost-effectiveness of weed control by predicting future yields using stand growth models, but over-simplistic assumptions inherent in this type of analysis (as outlined above) should be taken into account when the results are interpreted.

There is a need for further research into effects of site preparation on yield. Managers need accurate predictions of the effects of different regeneration strategies on a range of sites. These models should not only provide stand estimates of height, basal area, and stocking, but should allow managers to estimate variations in crop uniformity and stem form resulting from alternative strategies, as outlined by Whyte (1989). Given these predictions, they could make more efficient use of resources. Models of initial stand development would be practical first steps which may be partly achieved using existing data.

MODELS TO DESCRIBE CROP DEVELOPMENT ON EACH SITE

Mortality

Mortality of plantation- grown radiata pine between ages 0 and 5 is unrelated to stocking, and generally decreases with stand age. Young seedlings often die as a result of transplanting shock (Trewin and Cullen, 1985), and are most susceptible to agencies such as frost when they are small (Menzies and Chavasse, 1982). At Karioi Forest, for example, half the mortality recorded during the first 9 years occurred during year one (Mason *et al.*, unpubl. data).

Seedling mortality is a Poisson process, but the likelihood of death varies over time. Consequently, the probability of seedling death at any given juvenile age should follow a Weibull distribution (Taylor, 1974; Freund and Walpole, 1980) in which the C parameter should be less than one, since mortality diminishes with time.

Belli and Ek (1988) used an exponential decay function to model planted conifer survival in the Great Lakes Region of the United States. Their function was of the form:

$$S(t) = 100(EXP(-B*t^C))$$

where

$S(t)$ = Average survival percent at the end of year t.

t = Year, restricted to t = 1,2,3,4,5.

B and C = Coefficients, > 0.

The cumulative mortality (M(t)) at time t would therefore be:

$$M(t) = 100(1 - EXP(-B*t^C))$$

and the probability density function would be the derivative:

$$M'(t) = B*C*t^{C-1}*EXP(-B*t^C))$$

which is clearly a Weibull distribution. In all but one case, C was less than one. Where C was greater than one, mortality rate must have first increased and then decreased.

The parameters of the Weibull function for any given site and management strategy should be related to a variety of factors, including physiological and morphological plant factors, and environmental influences. These are discussed later.

Growth

A size distribution model of early growth could provide more sensitive estimates of growth rate and crop uniformity, thus enabling managers to better estimate how much to reduce initial stockings on any site. Further classifying stem by defect and size class jointly would allow more appropriate modelling of crop potential.

Measurement of diameter is difficult for young trees, but this need cause no difficulty during growth modelling. For the first few years, trees are too small to have diameters at breast height, and researchers often measure diameter 5 cm above ground level, making the transition to DBH when the trees are tall enough. Juvenile trees are essentially open-grown, and consequently there are exceptionally strong correlations between tree height and tree diameter. If models of height distributions were developed for very young trees, then DBH distributions at age 5 years could be predicted from them.

Diameter growth before crown closure should not be related to stocking as young trees do not compete with one another at the spacings employed in New Zealand's plantations. In a Nelder spacing trial in Kaingaroa Forest, with spacings varying from 620 to 12,000 stems/ha, diameter was not significantly related to stocking at age 4. By age 5, the relationship was significant, but even at that age, competition between trees was minimal for stockings below 1500 stems/ha (Tennent, pers. comm.).

The range in crop variability increases with time, but differently for individual sites and establishment strategies.

DIFFERENT SITES AND STRATEGIES

After planting, crops of the same initial size can grow and develop quite differently, depending on the microsite to which the trees are subject and the physiology and morphology of the seedlings (Figure 1). Ideally, a crop model should be capable of predicting seedling survival, stem defect frequency, and the rate of change in size class distribution parameters over time as a function of variables describing site and initial seedling attributes.

Site Attributes

Site attributes most likely to be related to the size class distribution parameters are listed in Table 1, under "base growth". Base growth is the growth that might be expected on unaltered sites. Many of these variables have been identified by earlier researchers as being related to radiata pine growth in empirical studies (e.g., Jackson and Gifford, 1974; Jackson *et al.*, 1976; Hunter and Gibson, 1984).

Trees' microsites are often altered by site preparation or post-planting treatments, and this complicates the predictive mechanism for models of initial growth. The four most common site preparation treatments are land clearing, cultivation, weed control, and fertilisation (Figure 1). All four treatments can have a significant impact on seedling survival, growth, uniformity and stem form (e.g., Hunter and Skinner, 1986; Mason and Cullen, 1986; Balneaves, 1988; Washbourne, 1978; Chavasse and Menzies, 1982). To attempt to build a model of the structure shown in Figure 1 would require far more detailed measurement of micro-environments and the effects on these of cultural treatments than is currently available.

The best alternative way to incorporate site manipulation into models could be to predict the effects of different treatments on growth, survival, and stem form based on site variables prior to treatment (Figure 3). This modelling strategy has worked for predicting effects of phosphate fertilisation on juvenile radiata pine growth from tests conducted on a soil samples (Skinner, pers. comm.). Subsequent growth can then be predicted as a function of base growth, plus or minus the effects of treatments adopted to manipulate sites.

Detailed studies of processes will be needed in order to make precise predictions of the effects of treatments on tree crops, but there may be some general trends in the existing database. Table 1 lists initial site variables which may be useful in predicting the effects of each treatment.

Weed control

Detailed studies of the effects of weeds on young radiata pine growth are needed before precise models can be constructed. Radosevich (pers. comm.) has demonstrated that weed species differ in their abilities to compete with Douglas fir in Oregon, and that visual assessments of the extent of weed infestation can be related to tree growth and development.

Meanwhile, some trends may be evident in the existing database in New Zealand. A brief look at the database has shown that, as expected (Waring, 1969), increased growth after weed control is a consistent effect in virtually all experiments, but it may be possible to derive more than simply a mean value. The weed species present were identified on some sites, and these may have differing effects.

Furthermore, the effects of weeds may be related to climatic and/or location variables. Where temperatures are near optimum for plant growth, and moisture or nutrients

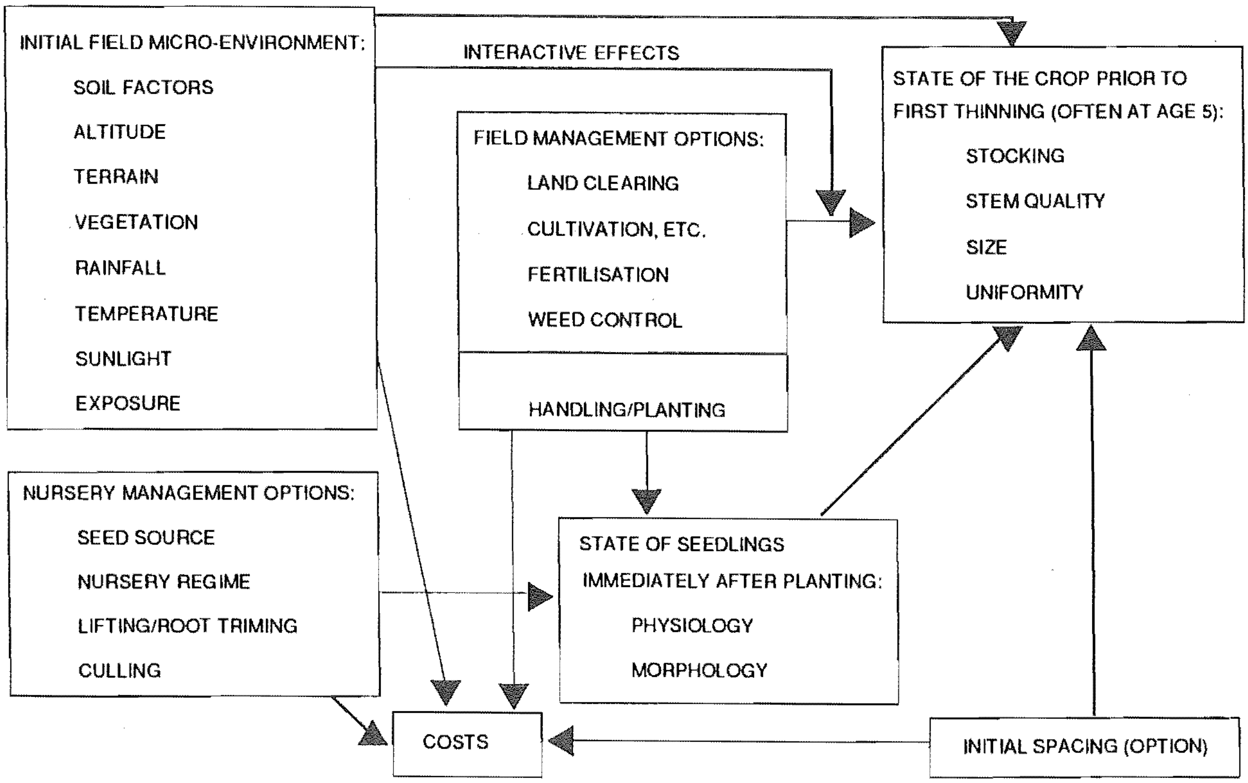

FIGURE 3 – Proposed model of forest plantation estate. Bold lines denote estimated effects.

are limiting, weed control may be particularly effective. Weeds are generally more prolific at lower altitudes and latitudes, and these variables may also be worth investigating.

Cultivation

Some general trends in cultivation experiments are evident, which may be quantifiable, but there remain some questions which demand process-oriented research. The largest increases in growth due to cultivation have often occurred on excessively wet sites with heavy soils, especially in Northland and Southland. In the central North Island, growth response to cultivation has been particularly variable (Mason and Cullen, unpubl. data), although ripping consistently increased root growth and stability of trees on compacted soils (Somerville, 1979; Mason and Cullen, 1986; Mason, unpubl. data).

Research is needed to identify soil tests which may be correlated with tree response to cultivation.

Fertilisation

Soil tests are routinely used in agriculture to identify the types and amounts of fertilisers required for crops. In addition to the phosphate test mentioned previously, there is potential to use measurements of total nitrogen as a guide for nitrogen fertiliser application in forest crops. For crops beyond the establishment phase, Hunter *et al.* (1986) found that response to nitrogen fertilisation was related to soil total nitrogen, Bray P extraction, age at fertilising (younger ages produced higher responses), the proportion of clay in the soil, and different pruning and thinning histories. N fertiliser on sites low in P was detrimental.

Boron deficiency is common in the Nelson region, and has been noted in Canterbury and parts of the Central North Island (Will, 1985). At present, there is no prospect of a soil test to predict boron deficiency (Skinner, pers. comm.), and local knowledge is probably the best indicator of crop response to boron fertilisation.

Potassium deficiency occurs in Nelson on ultra-basic "mineral belt" soils, and in parts of Northland (Will, 1985). Prediction of deficiency and effects of fertilisation might be made on the basis of region and soil type.

Variation in the effects of fertilisation with K or B on identifiably deficient sites is unlikely to be predictable with the existing database (Skinner, pers. comm.).

Magnesium deficiency commonly occurs after the establishment phase, and would not be included in initial growth models for radiata pine in New Zealand.

Land clearing

Land clearing can enhance survival of planted seedlings on frosty sites (Washbourn, 1978), and can lower site productivity where topsoil is removed (Ballard, 1976). As few data are available, it is not feasible to model effects at this time, but interim qualitative recommendations could be appropriate in the decision framework.

Interactions

The strongest interactions expected are between fertilisation and weed control (Mason *et al.*, unpubl. data). Interactions between fertilisation and cultivation are likely in Northland (Hunter and Skinner, 1986).

Seedling Quality

The enormous impact of seedling state after planting on tree survival, growth, and uniformity has been described by Trewin and Cullen (1985). Seedlings of high quality displayed higher survival and more rapid growth than adjacent trees of low quality.

Assessment of seedling quality is difficult. Traditionally, morphological characteristics such as sturdiness (height: diameter ratio), or root/shoot balance have been used. However, physiological characteristics such as root growth potential, water potential and nutrient reserves are also related to survival and growth (Menzies, 1988). To measure root growth potential, 28 days of growth under "ideal" conditions are required, yet transport from the field site to a glasshouse may markedly affect test results. Water potential can readily be measured on the field site with a pressure bomb, and nutrient reserves can be assessed through foliage sampling.

Assessment of planting quality is routinely performed by many forest growers as a check on the performance of contractors. Root placement can have a marked influence on juvenile tree stability (Mason, 1985).

Genotype, morphological and physiological quality, and planting practice, all affect the state of seedlings immediately after planting (Chavasse, 1980). Not only can these factors be difficult to measure, but they may interact.

When measurements of seedling quality become more refined, it should be possible to incorporate measures of quality in initial growth models. In the hypotheses described here, seedling quality would add to the residual mean squares of the models, but there is evidence that site variation and seedling quality do not interact. Trewin and Hunter (1987) found no interactions between seedling quality and site modification with fertiliser.

INFORMATION SOURCES AND TYPES

In order to decide on operations needed for establishing or regenerating a stand, managers draw on information from many sources. To predict effects of treatments, local experience is generally important, and actions which have worked in the past are often favoured, even though they may not be the most cost-effective. Windrowing is still used (Trewin and Mason, 1989), although it has been shown to be potentially harmful to sites (Ballard, 1976), and is more costly than alternatives such as burning or line blading. Similarly, on a site in the central North Island where a factorial experiment was located (Mason and Cullen, unpubl. data), the surrounding area was cultivated twice, and each tree fertilised with diammonium phosphate, a strategy which was costly, and gave low survival and growth. The most cost-effective site preparation, as shown by the experiment, was complete weed control using herbicides.

Qualitative information is often employed to make predictions; for example, the "frost flat" regime (Menzies and Chavasse, 1982), tree stock quality (Menzies, 1989), tree stock transport (Trewin and Cullen, 1986), and juvenile tree stability (Mason, 1985).

Qualitative information is also used to decide how to do certain tasks. The task of selecting herbicides, land clearing equipment, cultivation tools, and planting techniques is facilitated by information commonly available in handbooks or manuals (Preest, 1985; Davenhill, 1985; Levack, 1986).

Quantitative models are available to assist with some decisions as discussed previously (Skinner *et al.*, unpubl. data; Mason, unpubl. data).

DATA AVAILABLE FOR MODELLING EFFECTS

Many experiments have been established in New Zealand over the past two decades to compare establishment treatments, and these could be used either for further modelling of the response of trees to establishment strategies, and/or as a computer-based reference for local managers. A catalogue of 122 establishment-related, field experiments has been assembled. All these experiments began at establishment, and were measured to maximum ages shown in Figure 4. The variables measured are shown in Figure 5. In addition to those measured, soil and climatic data are available for most sites from public sources such as the New Zealand Meteorological Service and the Department of Scientific and Industrial Research Soil Survey (Table 1).

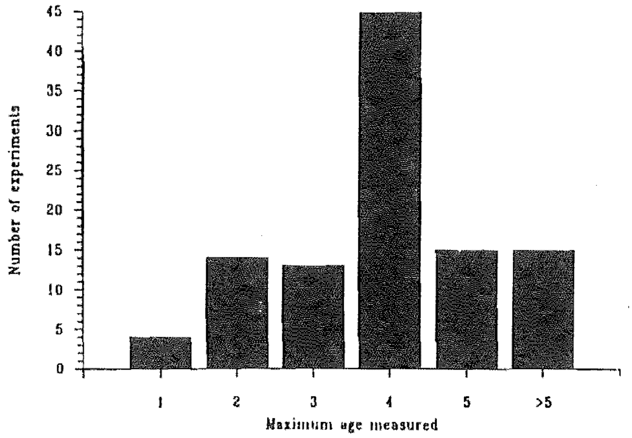

FIGURE 4 – Experiments available for establishment-related research

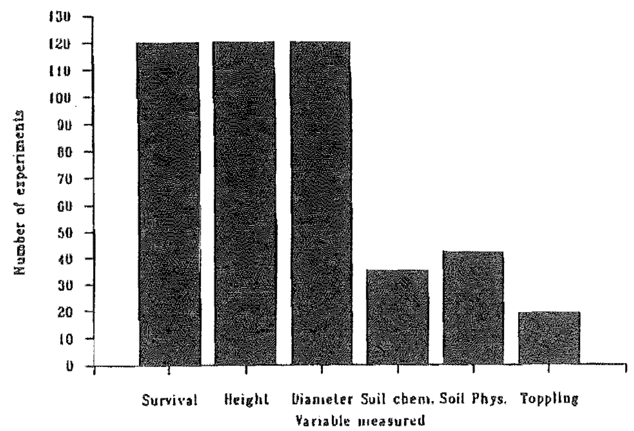

FIGURE 5 – Variables measured in establishment-related field experiments

Experiments with measures of soil chemistry were used to develop the phosphate fertilisation prediction model (Skinner, unpubl. data), which will also need to be validated. This could be done with existing experiments given appropriate soil analyses, assuming that undisturbed soil is still available from which to sample.

While the database provides a good starting point for model construction, it has several deficiencies which are listed below.

(a) Toppling has only been assessed in a few of the experiments. A toppling frequency model (Mason, unpubl. data) has yet to be validated. This will require further toppling assessment.

(b) The proportions of trees suitable as crop trees and with different types of stem defect have been measured in only 10 of the experiments, while 9 others have notations of stem defect only. More assessments of this type are needed.

(c) Locations of experiments and their multi-level treatments are shown in Table 2 (the regions shown relate to former New Zealand Forest Service conservancies). The locations are heavily weighted in the Auckland region, and fertilisation is disproportionately represented as a factor.

(d) There are too few experiments examining the effects of land clearing. Existing experiments might generate some local indications of effects, but none of the experiments include fire, the most popular form of land clearing (Trewin and Mason, 1989). It would be useful for managers to know how often windrowing causes the type of site damage reported by Ballard (1976), and this would require more experiments.

(e) Experiments with weed control as a factor are prevalent in Nelson Conservancy, but scarce elsewhere. This lack is most serious in Rotorua and Auckland Conservancies. A drawback of the weed control experiments is that no quantitative assessment of weed infestations were made.

(f) Table 3 shows the frequency of factorial experiments in the database. There are enough experiments to give an indication of the types of interactions which could be expected, but more factorial experiments estimating interactive effects of weed control, fertilisation, cultivation, and seedling quality are needed.

DECISION FRAMEWORK

In the near future, geographic information systems are likely to be used routinely to assist in management decision-making, and software will be required to summarise and use efficiently the vast amounts of information available. In fact, values of many of the variables listed in Table 1 will be available from such systems, and, in the absence of well-ordered decision frameworks, managers will be swamped with potentially useful information. An establishment/regeneration decision framework should incorporate the varied types of information and reasoning outlined in this paper.

The core of the framework would be a series of models describing the growth and development of radiata pine after different site preparation treatments on a variety of sites. Users would interact with the framework, describing their sites, and indicating the costs of options available to them. The framework would enable managers to evaluate the costs and benefits of alternative strategies, integrating as much relevant information as possible. The idea would be to use existing information to best possible advantage, and indicate where extra sampling (e.g., soils, foliage, etc.)

TABLE 1 – List of available site variables and possible correlations with growth, stability, and management effects

	Variable	Base growth	Topple freq.	Effects: Fertilisation	Effects: Cultivation	Effects: Weed control
Soil:	*Parent material	M		M		
	*Texture	P	M	M	P	
	†Resistance to pen.	M	P		M	
	*Dry bulk density				M	
	*Fertility rating	P		P	P	P
	*Response to P	P		P		
	*Carrying capacity	P			M	M
	*Topsoil depth	M				
	†Bray P (repeated)	P		P		
	*Total N	P		P		
	*Potassium	M		P		
	*pH	P		P		
	*Cation exch. cap.	P		M		
	*Tot. exch. bases	P		M		
	*Carbon	P		M		
	*P (various measures)	P		P		
	†Drainage rating	P	M	M	P	
	†Infiltration rate	M	M		M	
Climate	#Rainfall (Monthly)	P	P	M	P	P
	#Temperature (Monthly)	P			M	P
	#Frost incidence	P			P	
	†#Wind run	M	P			
	*Topography	P			M	
	‡Altitude	P	P	M	M	P
	‡Latitude	P		M		M
Cover:	†Weed types	P		P		P
	†Weed cover	P	P	P		P
	†Slash volumes	P		M		M

P = Probable correlation.
M = Possible correlation.
* Available from Department of Scientific and Industrial Research Soil Survey (DSIR, 1954, 1968).
\# Available from New Zealand Meteorological Service summaries.
‡ Available from New Zealand Department of Lands and Survey Information maps.
† Information not available for all plots.

would be most helpful. Emphasis would be placed on presenting information in the most useful form for managers.

Where models were unavailable, the system would allow interrogation of a database of experiments to see if any had been implemented in conditions similar to those described by the user, and description of the effects of treatments on early stand development in terms of size distributions and stem disorders. An equivalent knowledge-based record system describing clinical trials has been developed for oncologists (Rennels *et al.*, 1989).

Information on techniques and rules of thumb would also be presented where appropriate. This would cover such topics as herbicide use, land clearing machinery, cultivation, fertiliser application, and environmental implications.

TABLE 2 – Numbers of experiments by locations and factors

Factor	Auck	Rot	Well	Nels	Cant	West	Sthd	No. expts
Cultivation	19	13	4	0	2	0	2	40
Land clearing	1	2	0	0	1	0	0	4
Weed control	2	3	0	6	3	0	3	17
Fertilisation	28	7	3	10	11	16	12	87
None of above	5	4	0	6	0	0	0	15
No. of expts	41	20	5	16	11	16	13	

TABLE 3 – Numbers of factorial experiments

Type	Number
C*F*W*L	1
C*F*W	3
C*W	3
C*F	16
C*L	1
W*L	1
W*F	10
L*F	2

C = Cultivation.
F = Fertilisation.
W = Weed control.
L = Land clearing.

A combination of quantitative processing, qualitative processing and database interrogation is best implemented in the form of a knowledge-based computer system (or "expert system"). The important features of such systems are their ability to manipulate facts and rules as easily as numbers, capacity for working with incomplete or indefinite information, and transparency of reasoning to users (Stock, 1987). White and Morse (1987) have built a PC-based forest management expert system for aspen which makes full use of a geographic information system residing on a mainframe computer.

Two prototype systems have been built which relate to forest establishment in New Zealand. One is a herbicide adviser, which assists managers in deciding what herbicides to use given a weed complex, management strategy, and site variables. Recommendations are made which would kill all weeds possible, at a minimum cost. There is a need to extend this programme to a vegetation management approach.

The other prototype advises managers on tree nutrient deficiencies and fertiliser use. It can use information from soil analysis, foliage analysis, visual symptoms, and/or soil type in making recommendations, and incorporates the model developed by Skinner *et al.* (unpubl. data).

CONCLUSIONS

There are at least 122 experiments suitable for providing quantitative data to construct a model to characterise radiata pine initial growth and development throughout New Zealand. That number should be sufficient to provide a means for assisting in the choice of management strategies for some sites.

Effects of fertilisation and cultivation have already been widely tested, but more experiments examining the effects of weed control and land clearing techniques on crop survival, growth rate, uniformity, and stem form are needed.

Decision support models could usefully take the form of expert systems which incorporate analysis of experimental records, operational and costing information, and a geographic information system.

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DISCUSSION

Richardson –You say DBH is a function of height in young stands. What about the effects of weeds on diameter and height?

Mason - Different functions are needed where we have weed control.

Wilcox – New Zealand management practices are different from the natural biology of stands. Models assume divergence, and differ through regions.

Mason –Measurements at age 5 could assume parallelism.

Wilcox – Divergence could be achieved by adjusting time.

Weetman – This is very important in Canada. Companies have a lot of money involved in improving yield.

Mason –New Zealand spends a lot of time on manipulating sites.

Balneaves – We have developed tools, including land preparation, planting, and weed control. There is not usually a long- term effect of weed control or cultivation. What about the effects of harvesting on site productivity?

Mason – Older plots (12 + yrs) need to be monitored.

Balneaves –Will they be, given the change in FRI structure?

Mason – No, probably not.

Stand Establishment Research Needs in New Zealand

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ABSTRACT

In 1987, New Zealand nurserymen and forest managers were sent a questionnaire seeking their opinions on where future research on establishment and equipment should be focused. This survey elicited responses from those in charge of more than 940,000 hectares of the 1,154,226 hectare exotic forest estate in New Zealand. The survey indicated that an annual average of more than 30,000 hectares would be planted over the ensuing five years, 1988-1992.

In the nursery, inefficient seed utilisation was identified as the most pressing problem. Other areas of high interest were vegetative propagation and tree stock conditioning techniques. Field managers were most interested in identifying where savings could be made without jeopardising the future value of the resource, and identified weed control and land clearing as potential research areas. Improved dissemination of research findings also rated a high priority. There was no overwhelming unanimity of opinion, with some high interest ratings in all research topics.

Research needs identified by the questionnaire are examined and priorities for future research suggested and discussed.

KEYWORDS: Establishment, systems, research, operations, equipment, techniques, quality control, training, dissemination.

INTRODUCTION

Applied research is most likely to be successful when managers are involved in the planning process and researchers have good and regular contact with field operations. These two ingredients are essential for success in identifying research priorities and in getting research results speedily adopted by forest managers.

For this reason, a questionnaire was sent to all major New Zealand forestry enterprises in 1987, seeking managers' views on future forest establishment and equipment research. As a further guide to those setting research priorities, managers were also asked to state the extent to which they employed tools and techniques in growing forests. The questionnaire covered establishment techniques, and operational aspects of tree growing, up to but not including harvesting.

The Questionnaire Format and Analysis

The questionnaire consisted of four parts:

1. Operational statistics – the area administered by the respondent, and the estimated extent of operations over the 5-year period, 1988–1992 .
2. The level of interest in twelve nursery-related topics, with room for comments.
3. The level of interest in twelve field- related topics, with room for comments.
4. Space for any other topics which interested the respondent.

Levels of interest were indicated on a scale from 0 (no interest) to 3 (high interest).

The responses from nurserymen and field managers were analysed separately. Those from nurserymen were given equal weight. Averages were calculated for each topic, and relative frequencies were calculated for each interest level within the topic. These were plotted as histograms. Two analyses were performed on the responses of field managers; one weighted according to area administered, and one unweighted. Where there was duplication in the area administered, responses of the managers administering the smallest areas were removed from the weighted analysis. Comments on each topic were tabulated.

The Response

A total of 48 replies were received (Table 1). The responses came from 14 different enterprises, with regional distribution as shown In Table 2. This represents a response of approximately 81%, assuming a total national exotic forest estate of 1,154,226 hectares (Novis *et al.*,1988).

Table 1 – Respondents to Questionnaire

Respondents	No.	Land area (ha) administered
Nurserymen	10	–
Forest Managers	18	370,395
District Managers	16	528,523
Regional managers	4	119,408
Total area		1,018,326
Less duplication		73,349
Total area represented		944,977

Table 2 – Regional distribution of land administered by respondents

Region	Area (ha)
Northland/Auckland	134,071
Central North Island	523,900
Southern NI/Hawkes bay	63,928
Nelson/Westland	105,408
Canterbury	46,802
Otago/Southland	70,868
Total	944,977

Table 3 – Operations reported by respondents for the 5-year period of the survey

Operation	Area reported	Projected national total
Harvesting	16,545*	19,259^
Restocking	12,918	15,037^
New planting	16,150	18,799^
TOTAL PLANTING	29,068	33,836
Burning	13,935	16,221^
V-blading	5891	5891#
Roller crushing	1600	1862^
Manual clearing	1595	1857^
Windrowing	1530	1781^
Line blading	300	300#
Gravity rolling	200	200#
Rotary slashing	135	157^
TOTAL LAND CLEARING	25,186	28,269
Ripping	2945	3428^
Rip/disc	450	524^
Cultivation (Unspecified)	104	121^
Disc only	100	116^
TOTAL CULTIVATION (including V-blading)	9490	10,080
DUNE STABILITY	1070	1070#
Ground herbicide app.	14,635	17,036^
Aerial herbicide app.	16,686	19,423^
TOTAL WEED CONTROL	31,321	36,459
Low pruning	29,429	34,330^
Medium pruning	29,584	34,437^
High pruning	25,118	29,239^
Variable ht. pruning	320	389^
TOTAL PRUNING	84,451	98,395

* Assumed 500 cubic metres harvested per hectare, where only volume was reported. (This may account for the discrepancy between harvested area and re-established area, also some felled areas may be unsuitable for restocking.)

^ Assumed that non-respondents are doing similar amounts of each operation.

\# Assumed that non-respondents are not doing this operation.

Operations

Estimates of average annual harvesting and planting operations for the 5-year period were provided by all respondents (Table 3), although some preferred to give either the volume cut or the area cut, but not both.

Average Levels of Interest in Each Topic

The average levels of interest in nursery topics by nurserymen are shown in Figure 1. Sowing and seed losses were the topics of most concern, whilst alternative species, the outplanting system, and nursery cultivation were low on the list.

Field managers (Figure 2) were most interested in lifting and the outplanting system amongst the nursery topics, but their overall interest in this area was lower than that of nurserymen. It may be significant that the topics of most interest to field managers were those which are closest to the field in chronology.

The average interest of field managers in field-related topics is shown in Figure 3, whilst the forest area weighted averages are shown in Figure 4. It is clear that cost effectiveness, weed control, land clearing, and the research link

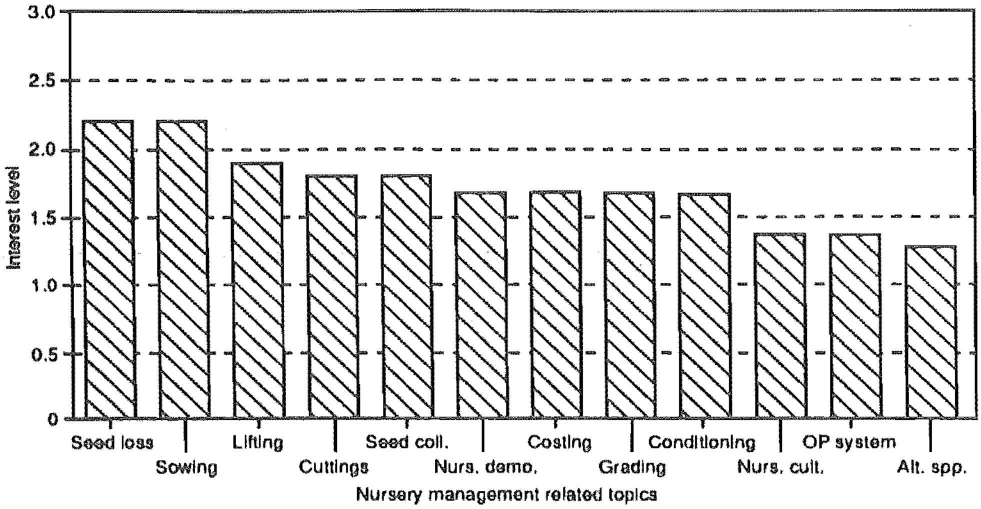

FIGURE 1 – Mean response from nurserymen to nursery-management related topics

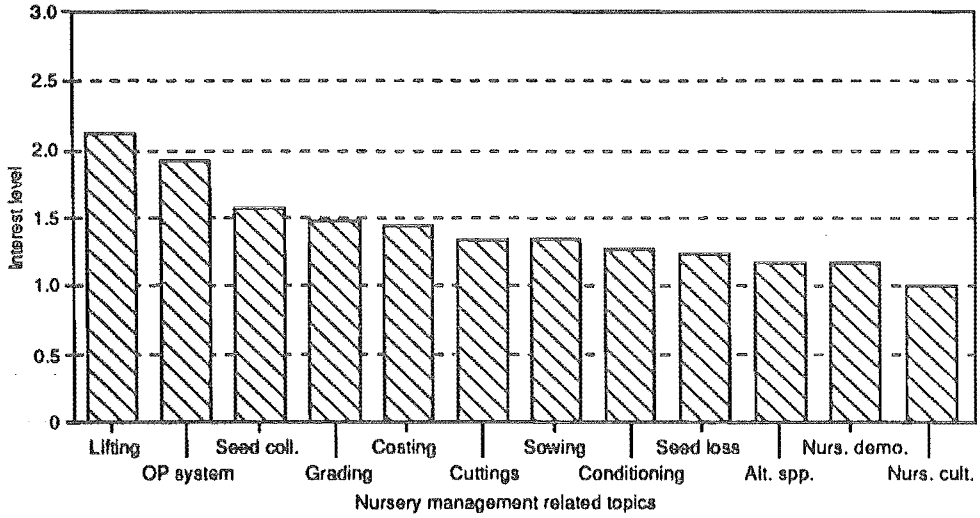

FIGURE 2 – Mean response from field managers to nursery-management related topics

bulletin are the items of most interest. Area weighting the response simply shifted the research link bulletin from first to fourth in the ranking. Planting and quality control are topics of least interest to field managers.

QUESTIONNAIRE RESPONSES (DISTRIBUTION WITHIN TOPICS)

Nursery Systems

Responses of Nursery Managers (in order of priority)

Seed losses after sowing: Respondents indicated that losses from bird predation and diseases were still very high. One nurseryman stated "I have done my best, but let's realise what this is costing and DO something." With the scarcity and high cost of genetically improved seed, nurserymen rated losses after sowing as their major concern.

Sowing, seedling emergence: The main concerns included precision sowing as it related to emergence, seedling quality, mechanical difficulties with the FRI-developed drum sower, and optimum spacing for different climates and species.

Also mentioned were: effects of nursery growth rates on subsequent field performance, i.e., fast growth in the nursery— does it indicate fast growth in the field; and a need for less sophisticated equipment for smaller nurseries.

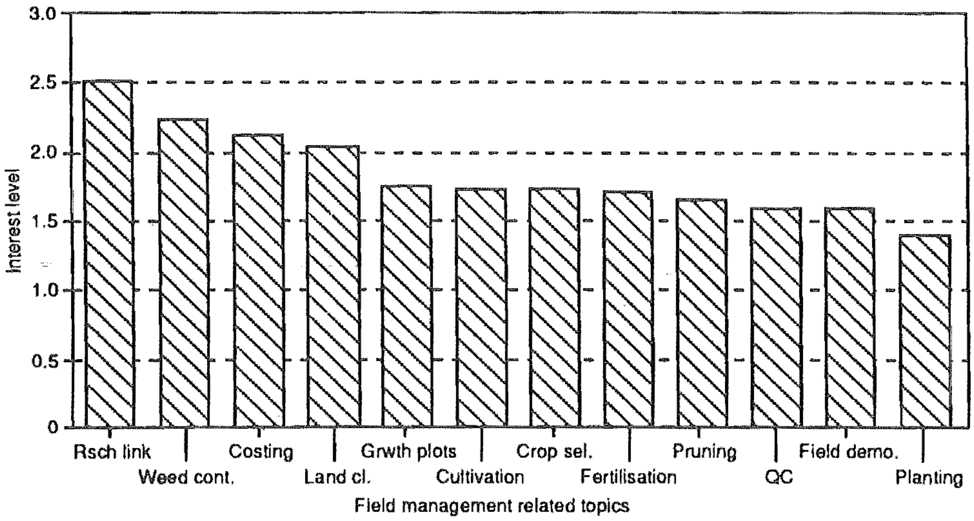

FIGURE 3 – Mean response from field managers on field-management related topics

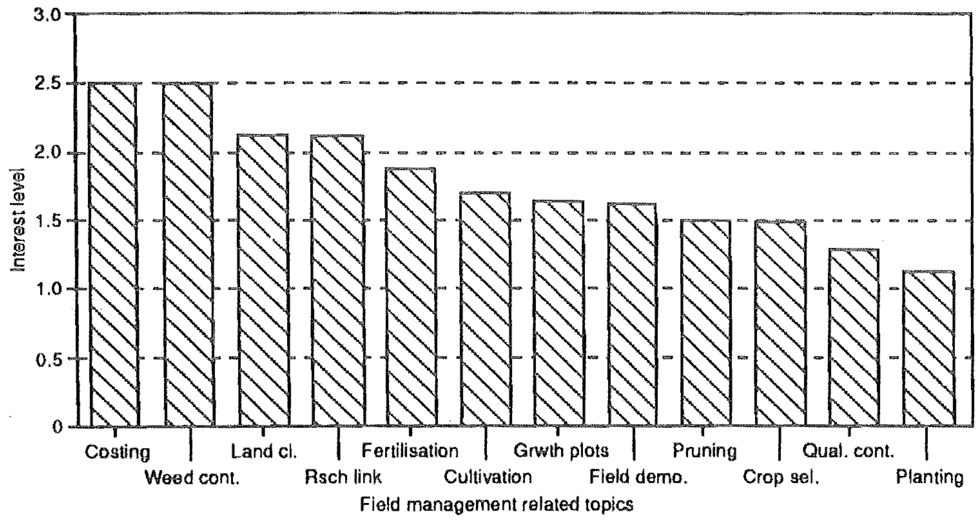

FIGURE 4 – Weighted mean response from field managers on field-management related topics

Seedling harvesting and packaging: Main interests were: develop systems for other species like the present radiata pine containerised method; continue previous work on developing alternative seedling harvesting and handling systems

Production of cuttings: A variety of areas were of interest: costs, stool bed production of cuttings, mechanisation of collection and setting, avoidance of juvenile form, less labour-intensive production systems. It was thought more work was needed on specialised species and problems relating to growing cuttings in different soil types.

Seed collection, grading: Main areas of interest were: grading, improved tree breeds, genetic quality of seed, seed collection, extraction, coatings to improve flow at sowing and a need for genetic material appropriate to different localities. A high incidence of *Diplodia* in seed orchards through severe picking, and the lack of a co-ordinated national seed grading system were mentioned.

Bare-rooted seedling conditioning methods: Effects of lateral root pruning across the bed (box-pruning) on field growth in relation to improved root form and tree stability, and nursery machinery to do the job, proved of most interest.

Information on new conditioning methods and less expensive machinery was requested.

Seedling grading: Most respondents stressed the importance of ensuring that only high-quality tree stocks were despatched to the field. They felt that seedling grading had a large influence on establishment success. In-bed grading needed to be promoted and optimum culling times established. Culling at lifting, with direct packaging, solved many problems.

Seedling production costs: Several respondents considered that alternative nursery practices had not been adequately costed; one respondent felt that nursery costs were so low that this did not matter. The questionnaire mentioned the use of containers (rootrainers, paper pots etc.) and some respondents indicated interest, especially for species other than radiata pine. Mechanised lifting to reduce seedling harvesting costs was also mentioned.

On-site demonstrations of new technology: Only three comments were received under this heading; they were all positive. One respondent felt that revision would be valuable, as there were many new and inexperienced people, while others wanted information on possible mechanised lifting and packaging systems to suit wet local conditions of 230 rain days per year.

Seed bed preparation: Comments favoured a continuation of current research, recognising that the size and configuration of nursery tractors are not optimum for this kind of work. However, one respondent felt that normal horticultural/agricultural type machinery was sufficient for small nurseries; there was also interest in deep ripping equipment for improved drainage.

Field-Related Operations

Responses of Field Managers (in order of priority)

Establishment costing: Respondents were concerned that establishment expenditure should be justifiable to accountants. Research is needed to provide information which allows managers to calculate the optimum level of establishment expenditure. There was a general feeling that more was spent than could be justified if the benefits of treatments were accurately estimated.

Weed control: There was widespread support for research on this topic, and it attracted more comments than any other part of the questionnaire. The general feeling was that weed control is a very important part of forestry, and that continuing research was needed to identify optimum chemical applications for the large variety of situations confronting forest managers. In particular, cost benefit analyses of weed control would be of interest.

Some of the main points of interest were: accuracy of aerial applications of weedicides, environmental impacts, increased sensitivity of the public to effects of weedicides, nursery applications, preplant and release sprays, gorse control, efficiency of equipment and setting up gear, screening and cost benefit analysis of chemicals, problems in second/third rotation crops, e.g., blackberry, and grazing for weed control.

Land clearing: The cost effectiveness of operations was the prime concern of respondents. There was increasing emphasis on restocking and advances in techniques to improve site quality and increase initial growth rates. Difficulties in site clearing by burning, due to reduced slash density, and in mechanical clearing and cultivation were mentioned.

Research link bulletin: Most comments were very positive. Respondents felt it was important to keep abreast of developments, especially with the recent reorganisation of MOF/DOC which has resulted in less circulation of personnel and associated regional experience. There was a feeling that poor dissemination of research results was a major failing. Details of current methods/research were requested. While there was majority support for a bulletin one respondent felt that there was no substitute for personal contact and that the Establishment Group had an important role as disseminators of new ideas to users.

Fertilisation equipment: Interest was generally high with comments on: identifying deficiencies, modifying nursery equipment, cost and benefits of applications, further work on aerial "flagman" system, comparisons between different aerial application methods—small and large helicopters, and a call for more information on, and an understanding of, factors which lead to a need for fertiliser application.

Cultivation and drainage: There was a call for continued development of systems and equipment. Ripping and other cultivation and land clearing operations were hindered by cutover stumps and slash. With increasing restocking of cutover, more information was needed on treatments for successful establishment, effectiveness of V-blading and ripping as they relate to growth, erosion and tree stability.

On-site demonstrations of establishment techniques: There was concern on how the "user pays" philosophy would affect future demonstrations. Demonstrations were a very useful way of getting the message across, especially for new developments. One respondent said interest was low because of perceived cost.

Pruning equipment: Mechanical pruning devices and equipment to suit proposed changes in pruning practice were major items of interest. Financial evaluation of techniques, to determine which stands should be pruned, needed further development.

Crop tree selection, toppling: Although the mean priority rating was relatively low, several respondents considered crop selection to be of major importance. Techniques and information were needed on: early identification of final crop trees, toppling on cultivated pasture, toppling as it related to different establishment treatments (e.g., stand density), planting methods, cultivation, remedial toppling treatments, and effects of wider initial spacing. With lower initial stockings, every tree needs to be a potential crop tree.

Quality assessment "indicator plots": Respondents indicated that they had their own quality control procedures, but would welcome ideas on how to assess new techniques. It was important to test and compare new and old treatments over a period of time. A standard format for such plots would be of value. Advances in treatments and techniques needed to be tested on a local basis. The variability of cuttings at planting and their validation versus seedlings on different sites in indicator plots was suggested.

Planting equipment: There was minimal interest in this topic. Spades for use on steep terrain, mechanised augers for containerised stock, toppling and planting techniques which give better and cheaper establishment were mentioned.

DISCUSSION

Scale of Operations

Respondents to the questionnaire were asked to estimate the average annual extent of their operations over the next five years, and the results are most enlightening.

Annual new plantings of over 16,000 hectares were significantly higher than might have been expected. Given recent restructuring of the forestry sector, the total establishment figure of over 33,000 hectares of young seedlings per year is certainly higher than most uninformed estimates. This equates to an annual requirement of about 40 million seedlings.

As expected, burning is by far the most commonly used land-clearing operation and more research effort should perhaps be put into this important area. V-blading is surprisingly popular. On central North Island pumice country, V-blading is now routinely used for cultivation and first-year weed control on frost-prone sites. Most respondents who indicated that they employed ripping are also likely to employ mounding discs behind the ripper tine. As expected, weed control is widely used, and over 35,000 hectares are treated annually.

Pruning is more widely practised than expected. Past estimates have been considerably lower than the areas reported. On the basis of the reported areas, some very rough estimates of total expenditure on different operations can be made.

These estimates are based on 1987 prices of operations to forest managers. In today's economic climate, contractors are tending to underprice their tenders to ensure short-term survival. Ultimately, the cost of machine replacement will have to be borne by the industry, and prices will rise significantly in real terms.

Nursery Management

Nursery managers were primarily concerned with seed losses. This was reflected in the high interest shown in sowing and losses after sowing. It has been estimated that only 50% of seeds sown result in useable seedlings, and, with the scarce genetically improved seed resource, an improvement in the seedling:seed ratio would be of considerable value.

However, not only seed is lost. Non-emergence and bird predation on seed result in large areas of unused seedbed, and therefore increased costs of sowing, conditioning, fertilisation, and nursery pest control.

Many nurserymen have ideas on how they might reduce predation, but no-one knows what is really going on from a national perspective, nor what techniques work in any given set of circumstances. Netting is used to protect scarce genetically improved seed/seedlings from birds, but would prove very costly for large-scale sowings.

There was interest in box-pruning as a conditioning method and especially as it relates to machine lifting. The high level of interest in seedling harvesting and packaging was perhaps a result of past extension work, although managers may be interested to see cost/benefit comparisons of different lifting and handling systems.

Research into cuttings production techniques and equipment was rated reasonably high priority, and reflects the fact that this is a new process for most nurseries. It is now felt that vegetative propagation may be the most economical way of producing genetically improved tree stocks on a production basis.

Field Management

Forest managers were most concerned about costs. More specifically, they wished to know what establishment treatments are worth at the end of the rotation. This was reflected in comments on every section of the questionnaire.

The interest in weed control is generated by the annual cost of the operation, the complexity of the subject, and perhaps a need for dissemination of past research, since many of the questions posed in the comments section have been answered by researchers.

Land-clearing methods were also perceived to be a high cost. Managers are increasingly faced with re-establishment, and they wish to find ways of reducing clearing costs. Economic analysis, long-term effects on site productivity, and the risks associated with V-blading on compact sites need further work. In addition, the effects of large V-bladed mounds on costs of silviculture and harvesting operations and on long-term site quality, need to be assessed.

The annual expenditure on pruning is greater than the expenditure on all other operations put together (Table 4), and it is surprising that pruning research received such a low rating. This may be because managers regard use of current hand tools as the most efficient methods possible. However, some managers were interested in attempts to make the operation more efficient.

Expenditure on cultivation other than V-blading is low, and the lower level of interest perhaps reflects this. We are still unable to adequately predict the wide range of responses to cultivation which have occurred around the country.

It has been estimated that 20% of all seedlings planted topple to at least 15 degrees from vertical during their first 5 years in the field. Given the costs associated with this, it is surprising that planting methods, crop-tree selection and toppling were rated so low a priority. Also, large areas of more mature trees are damaged by high winds which are common in New Zealand.

Table 4– Expenditure on establishment operations

Operation	Estimated annual expenditure
Planting (incl. tree stocks)	$6,000,000
Land clearing	$5,000,000
Cultivation (incl. V-blading)	$1,500,000
Weed control	$7,000,000
Pruning	$25,000,000

CONCLUSIONS

1. Future plantings are likely to relate closely to harvested areas which are scheduled to increase rapidly in the near future. There has been relatively little research on effects of different harvesting methods on subsequent re-establishment success, or of establishment and restocking treatments on harvesting techniques. There is a need for better integration of harvesting and replanting operations to increase efficiency and reduce environmental impacts of conversion from old to new tree crops. Ideally, land clearing for restocking would be a charge on harvesting. This should encourage the harvesting of smaller piece sizes which are currently left as slash and impede subsequent replanting and maintenance operations, thereby raising growing costs.
2. Nurserymen regarded seed losses as the most pressing problem in nurseries. Tree-stock conditioning methods, seedling harvesting, and cuttings production were regarded as areas where research is required.
3. Forest managers were most concerned about the cost effectiveness of their operations, and wished to know where they could make savings without compromising the future value of the resource. To this end, weed control and land clearing were identified as the most favoured areas for future research.
4. More than 90,000 hectares are pruned each year at a cost of approximately $25,000,000. This is the largest single cost of all the operations surveyed, and may represent a fertile area for cost-effective research.
5. There was overwhelming support for an informal bulletin to disseminate establishment research findings to managers.

Research Priorities

There are large gaps in knowledge on plantation re-establishment. As replanting follows harvesting, the need to integrate these operations carefully to complete cropping cycles and eliminate weaknesses for sustained yield management is evident. Traditionally, logging and replanting have been viewed as two separate operations so that there is some difficulty in bringing harvesting and establishment managers and researchers together.

Harvest residue (slash) causes establishment problems and is generally burnt. Burning is now less environmentally acceptable and so other site-clearing methods need to be developed. V-blading of slash into soil mounds is popular, as it is relatively cheap and combines land clearing, soil cultivation and weed control. However, large soil mounds are likely to hinder extraction of thinnings and final harvest operations. Also loose soils, particularly over hard ground, will provide poor anchorage for tree roots. Toppling in young stands and windthrow in older areas degrade wood quality and final crop values (Mason and Trewin, 1987).

With the introduction of faster-growing genetically improved radiata pine tree stocks with high GF (growth and form) ratings, there is concern amongst field managers and establishment researchers that current nursery conditioning practices (root pruning and wrenching) are too intensive. They promote the development of a compact mass of fibrous roots which encourage fast initial growth and promote toppling. Large-diameter tap-roots and lateral roots which anchor self-sown trees firmly (self-sown trees rarely topple) are replaced by small-diameter roots which have difficulty in anchoring fast-growing tops (Trewin and Menzies, 1989). Cuttings with some physiological age (more than 2 years from seed) have been shown to topple at half the rate of seedlings (Klomp and Menzies, 1988). However, until such time as the cost of cuttings can be reduced, (seedlings are currently half the cost of cuttings) efforts to improve stability of bare-rooted stocks must remain a high priority.

Areas prone to wind-damage should be identified, and classified according to risk, so that these can be eliminated from restocking programmes or planted up with wind-resistant cuttings or seedlings (appropriately conditioned strong rooting breeds). Also, some site cultivation treatments have been shown to increase the likelihood of toppling (Mason, 1985) and need further evaluation. It is suggested that radiata pine genotypes with strong rooting characteristics be selected and more research done on effects of nursery conditioning, root-trimming, site cultivation, planting methods, and fertilisation, and on root development in relation to wind firmness.

Toppling prevention and remedial treatments, together with their effectiveness and cost, need to be assessed.

Until these questions are answered, the planting of faster-growing, highly rated new G.F. breeds on high-fertility sites should be viewed with caution. New Zealand is a windy country and more emphasis needs to be placed on developing breeds and silvicultural practices which will ensure that plantations are less susceptible to the degrading effects of wind on logs (butt sweep, sinuosity and stress wood), and windthrow which can have drastic effects on crop values.

There is some concern that the trend towards lower stockings may be premature as there is still a large gap in knowledge on radiata pine root structures in relation to genetic characteristics, nursery conditioning, and soil compaction levels in cultivated and uncultivated ground.

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APPLICATION OF KNOWLEDGE-BASED PROGRAMMING TECHNIQUES TO COST-EFFECTIVE SELECTION OF HERBICIDES IN FORESTRY

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ABSTRACT

Knowledge-based programming techniques were employed to build a PC-based system for selecting herbicides, to improve the cost-effectiveness of vegetation management regimes and increase users' awareness of environmental hazards. The strategy used to develop the tool is explained, and the structure of the system described. It is written in PDC Prolog, and incorporates both knowledge-based and traditional procedural programming structures. The program is very user-friendly, with capabilities specifically relevant to forest supervisors. It may be adapted to different localities and herbicide/weed regimes without further programming. The benefits of having this kind of decision-support tool in managing plantations with the intensity and sensitivity needed today are discussed.

INTRODUCTION

A vegetation management adviser is one essential component of any forest management decision-support system, and knowledge-based programming techniques provide an excellent way to accomodate such a tool. Jeffers (1989) and Mason (1989) outlined the form which future computerised decision-support systems may take in forestry. User-friendly, comprehensive and malleable environments are possible, within which managers can select the types of analyses they desire. These environments may comprise geographic information systems, growth and yield models, other stand models, forest-level models (simulators, linear programming, and dynamic programming combinations), and other such useful tools. It is knowledge-based programming, however, which enables full integration of the tools, and which fills the gaps hitherto occupied by handbooks, rules of thumb and/or experts.

Knowledge-based programming is a name given to a set of computer programming techniques which enable machines to represent and process qualitative, symbolic information in a logical way. Saarenmaa (1989) comprehensively outlined these techniques within a forestry context. Several varieties of knowledge-based programming are available, but the two most commonly employed in everyday applications are rule-based systems and object-oriented programming. Expert systems are a subset of knowledge-based programming applications.

The vegetation management components of forestry decision-support systems are best implemented in a knowledge-based structure. Design of vegetation management strategies or "regimes" involves many non-numerical analyses. Experienced managers acquire a qualitative understanding of the components of the problem: for example, susceptibility of weeds to different herbicides; times of year weeds are physiologically active; behaviour of weeds following alternative treatments; effects of different weeds on tree crops; and so on. This type of knowledge currently defies numerical analysis.

WHY BUILD A VEGETATION MANAGEMENT ADVISER?

Criteria for expert system domain selection

Stock (1987) proposed the following seven criteria for a suitable expert system domain, which term in this context means "knowledge area represented". Designing a vegetation management regime meets these criteria.

1) Expertise should be scarce and time consuming to learn, but the task should take only a few hours or days.

   Tasman Forestry Ltd., for example, employs an expert (D. J. Geddes) in vegetation management, who acquired his knowledge from many years of field experience. Field supervisors vary in their abilities to design cost-effective vegetation management strategies, and often rely on the recommendations of a single expert within the organisation. During a test at Tasman Forestry Ltd., supervisors prescribed treatments in response to the same weed problems: their solutions varied in cost by a factor of three (Geddes pers. comm.). In some cases the treatments would have been unnecessarily expensive, whilst in others they would have had a low level of control.

2) The problem domain should be narrow, but deep (highly specialised), and there should be a large number of possible solutions.

   Forest managers proficient in the design of vegetation management regimes are specialists with an in-depth understanding of the biology of local weed species and the effects of many treatment alternatives. Different chemicals, and/or different physical treatments are available, as set out by, for example, Preest (1985), Davenhill (1985), and Preest & Davenhill (1986) for the New Zealand scene. When these are considered over a range of weed species, environments, and seasons, the number of possibilities is large.

3) The problem solution should require heuristics (rules of thumb), ie: a set of equations could not be used to arrive at a satisfactory solution.

   Given the range of qualitative rules required for effective design of vegetation managment regimes, it is unlikely that a set of equations would be adequate. In part this is because models of weed behaviour are almost entirely qualitative, and strategies for their control have often arisen from field experience rather than from quantitative research.

4) Competent experts must be available and willing to help with development.

   In the system described here, one company expert (D. J. Geddes) and one research expert (N. A. Davenhill) were much involved in pooling their knowledge and interpreting knowledge stored in data-bases.

5) The problem should be financially important enough to warrant building the system.

   Based on responses to a questionnaire which asked for areas to be treated, it was estimated that New Zealand's forest industry planned to spend approximately $7,000,000 annually on vegetation management between 1987 and 1992 (Trewin & Mason 1989). The direct costs of effective vegetation management can vary from just a few tens of dollars to several hundred dollars per hectare, while the opportunity costs of misapplication of techniques can be very high, in the form of poor subsequent crop performance, or as unnecessary expenditure.

6) Experts in the area should agree.

   In New Zealand there is general agreement among experts about the broad principles of vegetation management regime design. Davenhill and Geddes occasionally differed in opinions but only on points of detail.

7) Ample data, test cases, and potential users should be available for testing the system.

Data, test cases and users were all available. Geddes (1987) had compiled a very complete vegetation management manual for Tasman Forestry Ltd., and the company's forest supervisors were keen to help with the project.

Environmental hazards

Herbicides vary in their impact on the environment (Adams, 1988), and managers should avoid using particular products in circumstances where their use may pose a risk to adjacent crops, wildlife, fisheries or people.

A computerised vegetation management adviser could accurately and quickly alert supervisors when use of a herbicide may be risky. In the system described here, warnings of potential hazards are brought to the user's attention when a herbicide is selected, and toxicity information is available at the touch of a key.

Training

For inexperienced supervisors, a decision-support system could be used to assist with training. It is difficult for them to cope with the wide range of substances, application rates and methods, non-chemical control methods, responses of weeds, and costs involved in vegetation management. A computerised system can make the problem more manageable, without removing them from the decision process.

Identification of gaps in knowledge

When knowledge is collated within a decision-support package, it is common that important gaps in knowledge are highlighted. It was therefore expected that the project would identify research opportunities.

Component of a comprehensive decision support system

Future forestry decision-support systems are likely to comprise a range of models, tools, and databases, and a vegetation management adviser was deemed to be an important component of such a system. As this was the first knowledge-based application implemented by Tasman Forestry Ltd., it would serve as an indication of the potential for such systems.

CONSTRUCTION METHODOLOGY

Construction of the system proceeded in four distinct stages: an initial protoype; knowledge acquisition; coding; and a testing/adjustment cycle.

Initial prototype

A small prototype system was devised as a result of a brief meeting with Tasman Forestry Ltd. staff, based on some information contained in the firm's Weed Control manual. This was a crude program, written in BASIC, which contained knowledge of three weeds and ten herbicides. It served to illustrate the potential for a knowledge-based system, and it elicited specific suggestions for improvements.

Knowledge acquisition

Further knowledge about the topic was acquired from two sources: (i) the full extent of Tasman Forestry Ltd.'s weed control manual, and (ii) a series of interviews with Tasman and Forest Research Institute staff, particularly D.J. Geddes.

The weed control manual had been compiled by Geddes (1987) from a range of sources, predominantly information from research conducted at the Forest Research Institute about herbicide treatments. Specific treatment information was neatly summarised in a two-way table of herbicide rates, with weeds on one axis and chemicals on the other.

The interviews were conducted over a two week period. A typical interview, which would last for 3-4 hours, covered topics ranging from general overviews of the subject to specific attributes of weeds, herbicides, surfactants, and other such detailed experience. Each interview was taped, and later transcribed. The transcription process ensured that nothing was missed, reviewed the material covered, and identified topics for future interviews.

Coding

The programming language chosen for the task was PDC Prolog (Prolog Development Center 1990). PDC Prolog can be implemented under several operating systems, and has many desirable attributes for knowledge-based programming.

Coding of the first full system, labelled version 1.0, was conducted over a period of 13 weeks.

Testing & adjustments

Version 1.0 was evaluated by Forest Research Institute staff, and subsequently, after some adjustments, by Tasman Forestry Ltd. staff. There followed an iterative process of evaluations and coding adjustments. Total coding time for the current system (version 1.23) amounted to 18 weeks.

STRUCTURE OF THE PROGRAM

Overview

The system is constructed as what is called a "domain- specific shell" (Menzies 1989; Mason 1989; Knaus & Blecker 1990). Algorithms required for herbicide selection are in compiled code, as are structures for representing different sorts of herbicides, weeds, surfactants, application methods, and their interactions. The information which makes the system specific to any given region, however, can be added to, changed or removed without further coding in Prolog.

There are two programs; one for inputting knowledge (Vegetation Management Adviser), and another for retrieval and analysis (Vegetation Management Tools). A conceptual structure is shown in Figure 1, the structures in which are described below.

User interface

The user operates the system through menus, input screens, editors, and an on-line help system which is sensitive to any specified context. The help system is extensive and complete, to the extent that a manual is not needed. Wherever possible, input is by means of menus. Input screens consist of sets of fields, usually associated with a frame, as described below.

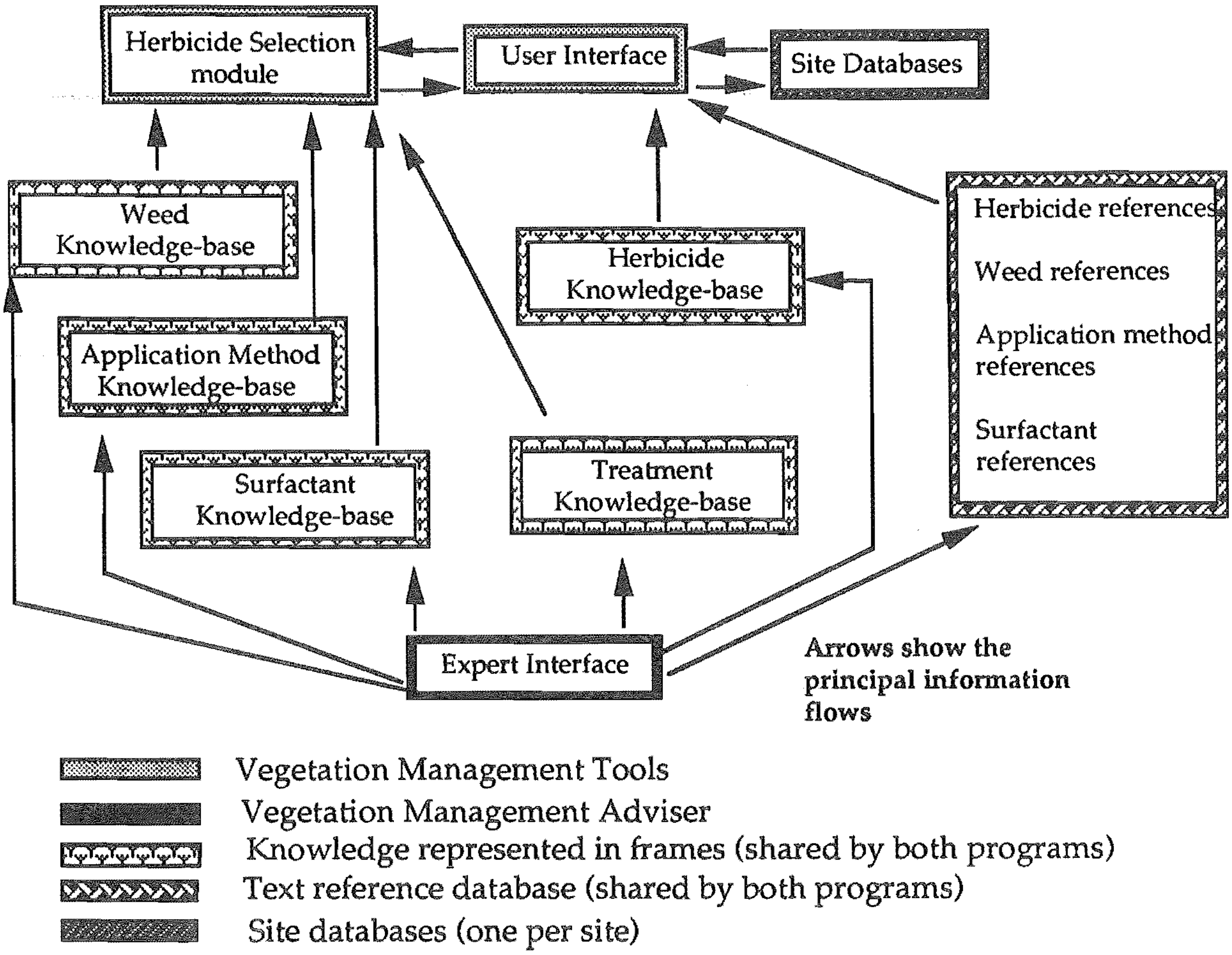

Figure I Weed Control Decision-Support System

Knowledge-bases

Knowledge which can be updated is stored in structures which are known as frames (Minsky 1975; Jay & Knaus 1989). These are structures which contain attributes and describe behaviours associated with particular types of objects or relations. Attributes and behaviours are stored in locations called slots. For instance, the application method frame has slots for the method name, the coverage of chemical mixture per hectare or per tree, the default cost per hectare, the cost if trees are shielded (protected from the spray), whether the method can be used after planting, a device name, and several variables associated with the device if it is named. Two different types of data can fill the coverage slot, identifying whether the value is per hectare or per tree. Similarly, if an application device is named, this indicates that the application method overrides a default value for the amount of water in a mixture (defined in another frame), and the other variables associated with the device define how this should occur. All herbicide application methods can fit into this frame, and their behaviour is defined by slot values.

Frames are used to store knowledge of weeds, herbicides, surfactants, application methods, and potential herbicide treatments for three different physiological states of each weed ("juvenile", "mature flushed", and "mature dormant").

Text references

System references consist of simple text information, describing weeds, herbicides, surfactants, and application methods. These can be input using Vegetation Management Advisor, and can be accessed by users of Vegetation Management Toois whenever they are relevant to decision-making. The references are stored in databases set up for use on a local area network.

Herbicide selection

Herbicides are selected by a module which uses a set of rules and a numerical procedure. The rule-base decides which treatments would affect the weed populations on any given site, and makes any necessary adjustments to chemical mixtures based on information contained in the frames. The effects of all treatments which fit the site, user-defined actions, the set of weeds present, and time of application are evaluated, and the results compared. The system maximises weed kill multiplied by a weighting of the importance of each weed, plus the period of germination inhibition, all divided by the cost. Users can alter the treatment selection criteria by defining the relative importance of weed kill, antigerminant action, and cost.

USING THE SYSTEM

Expert module

The expert module (Vegetation Management Advisor) is used to specify, for a given locality, the attributes of weeds, herbicides, surfactants, application methods, and their interactions. Each of these frame instances is entered on a screen with fields. Some fields have menus associated with them, some are altered simply by pressing "enter", while others ask for specific input.

Throughout the program, help can be accessed by pressing the F1 key, and menus are used for input wherever possible.

After frame instances have been entered, text information can be entered in an editor. When it is relevant to decisions, this text will be accessible from the user module.

User module

From the first menu in Vegetation Management Tools a user can: access any text reference; access chemical toxicity information; press F1 for help; or go to a set of utilities which allow site definition and treatment selection.

To define a site, the user selects the weeds present from a menu, and is then taken to a screen with a set of fields. Many of the field values are nominated by the system from knowledge contained in frames, but this information can be overridden if the user so chooses. Fields in which users must supply information are the percentage cover of each weed, the average height of each weed, the season, and whether each weed should be killed or saved (in some circumstances, killing of one weed can result in a worse infestation of some other, more damaging weed). If nothing is entered in the crop height field, then a pre-plant situation is assumed. Text references relating to a weed can be accessed by placing the cursor in a field with the name of a weed, then pressing F1. After a site is defined, it can be saved to disk.

To select a herbicide, the user presses F2, and the system asks what relative weights should be placed on weed kill, antigerminant action, and cost of treatment. Other questions relating to the site are posed if relevant.

After a herbicide is selected, the user may be warned of an environmental hazard. If not, or if he/she elects to proceed anyway, the system displays the best-known herbicide treatment, along with the predicted results, and the time for the treatment to take effect. If more information about the herbicide, surfactant, or application method is desired, the user can place the cursor in the appropriate name field, and access text references.

The user can then reject or accept the treatment. Acceptance causes an updated site screen to appear. If the treatment is rejected, the original site screen is presented, and further treatment selections will ignore the rejected treatment. If desired, a hardcopy prescription sheet can be printed.

GAPS IN KNOWLEDGE

Construction of this system highlighted gaps in knowledge of vegetation management. For effective vegetation management regimes to be designed, accurate models of site behaviour under different types of treatments should be developed. Two of the most important areas for research are weed biology, and crop response to removal of weeds.

Weed biology

Provision has been made within the program for recording of weed characteristics such as relative competitive ability, reproductive ability, and weed growth rate. Studies in the central North Island have been designed to measure some of these attributes (B. Richardson pers. comm.).

Crop response

The responses of forest crops to competition and the competitive influence of crops on weed growth on a range of different sites are important components of a site model. A model of *Pinus radiata* growth and response to weed competition from ages 0 to 5 years in the Central North Island region has been constructed from historical data (E.G. Mason, PhD thesis at University of Canterbury, in prep). The model includes effects of variations in site and treatment factors. Experiments with more specific measures of weed competition are required for model refinement.

The responses of older crops to competition need to be quantified, so that the harvestable benefits of vegetation management can be included in decision-making.

FUTURE PLANS FOR THE PROGRAM

Cut-down version for general use

Interest has been expressed by parties outside the forest industry in a version of the program which does not specifically assume any particular type of crop. The user would simply say which plants should be killed on a site, and which saved.

Regime selection

There is a need for a system which will include physical control methods, and which selects an optimal sequence of vegetation management treatments over several years.

Two ways have been identified to achieve this. With both, an attempt would be made to minimise competition over time per unit cost of treatment.

With existing information, a rule-based module could simulate the treatment selection activities of a current human expert.

The second alternative would be more robust, and would include an accurate site model. The module would extend the existing frame-based structure of the program, and would employ model-based reasoning (Koton 1985; Fulton & Pepe 1990). An object-oriented version of PDC Prolog is under development, and it is anticipated that this would cut development time considerably.

THE COSTS AND BENEFITS OF CHANGE

Computer systems are changing the way we live. The arrival of the fifth (artificial intelligence) generation of computers has been likened to the change from primitive to advanced industry in the late 1880's (Winner 1984). This has brought about significant redefinition of social relationships. Many similar changes due to artificial intelligence may be forseen (Laulan 1986). Office automation has already led to a decentralisation of management structures, and the expansion of information and service economies (Pohl 1984). Winner (1984) predicts a rise in the status of the managerial class, and a decline in that of professionals.

Many ethical questions relating to artificial intelligence applications remain to be resolved. Should people be displaced by machines (Michie 1982) and, if so, how should wealth be distributed to humans (Moshowitz 1984)? If a network of "intelligent" programs makes a mistake, who is responsible? How should perverse military uses of artificial intelligence be regulated? Concerns such as these have even led to a suggestion that artificial intelligence might be immoral (Le Chat 1986). Weizenbaum (1976) feels that forms of "unreason" are important in decision making, and that computers should not be allowed to perform some tasks, even if they are nominally capable. It is not intended that these issues should be resolved here, but managers should be aware of their existence and relevance.

Forest managers have much to gain from knowledge-based tools. Most importantly, they can expect to have access to more comprehensive, up-to-date information, summarised and presented in a manner appropriate to any particular decision, at greater speed and with higher accuracy than ever before. This should result in more efficient use of managers, and better decisions.

The financial costs of implementing these systems are small compared to potential benefits. The system described here cost several thousand dollars to implement, but this investment might be recovered from just one significant improvement in herbicide application on a reasonably large block of land. A change in a choice of chemical resulting from a warning of an environmental hazard might save many thousands of dollars in legal fees and damages.

CONCLUDING REMARKS

Development of this system has demonstrated some opportunities for the forest industry in the emerging field of knowledge-based programming. It is anticipated that forest managers will enjoy increasingly sophisticated support for decision-making from these sorts of systems in many of the diverse facets of our profession.

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PLANNING AND CONTROLLING ESTABLISHMENT AND EARLY GROWTH IN NEW ZEALAND

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ABSTRACT

Two computer-based tools have been built which provide a basis for helping managers to make sound decisions at time of establishing radiata pine and in the first few years of a crop's life in the Central North Island of New Zealand. One is a model of initial radiata pine growth that is sensitive to changes in site quality induced by both natural influences and site preparation methodology. The other is a knowledge-based system designed to assist with selecting herbicides for vegetation management. The natures and capabilities of these tools are described within the context of a management system, and opportunities for their incorporation into a comprehensive management decision-making and control system are discussed.

INTRODUCTION

This paper is concerned with providing tools to assist decision-makers in planning and controlling the establishment and early crop development of radiata pine in the Central North Island of New Zealand. There are considerable numbers and kinds of operations that could be prescribed at the beginning of any plantation crop. If a successful combination is chosen and implemented, the financial and managerial benefits right through its production cycle can be very considerable. On the other hand, many of the operations can be individually expensive and in aggregate their cost could be excessive. Managers need ways to decide, therefore, what cultural operations are the vital ones which produce positive qualitative and financial returns on any given site.

Recent advances in power and availability of computers provide opportunities for forest managers to improve their access to detailed information directly relevant to making such decisions and their implementation. British information technology researcher Chris Morse pointed out that in 1980, a 4.5 mips computer cost the equivalent of 210 middle-management salaries. By 1990, this had fallen to between two and six salaries, and by 2000 it is predicted to be only one eighth of a salary (Jackson 1991). The implications of this for forestry are that managers can have access to dedicated, powerful processors, and are therefore in a position to benefit from increasingly sophisticated computer-based tools. Developments in programming methods have also facilitated the creation of these tools. The potential for these improvements is demonstrated here.

Many of the most useful new programs are likely to incorporate artificial intelligence, especially knowledge-based programming, of which expert systems are a subset. Knowledge-based programs incorporate domain-specific information, both quantitative and qualitative, in a form which allows sophisticated processing of that information. Knowledge-based programming departs from traditional scientific methodology, in that it focusses on the use of uncertain or incomplete information, and its modelled capability is more likely to come from interviews of applied experts than from scientific studies (Stock 1987). Saarenmaa (1989) provided an excellent overview of these techniques in a forestry context, and Mason (1989) discussed their relevance to plantation forestry in New Zealand.

Plantation establishment is a field with great potential for such tools, for it often involves the use of rules of thumb, and the value of alternative techniques has traditionally been assessed by managers with local experience, rather than through the use of quantitative, scientific models. A notable exception is in the Great Lakes Region of the United States of America, where models of initial survival and height growth have been built for two conifer species following a range of optional site preparation treatments (Belli & Ek 1988).

Two computer-based tools have now been developed here in New Zealand with a view to providing the best possible objective basis for decision making prior to and in the first few years of a radiata pine plantation. The first to be described is a model of the survival and growth of radiata pine immediately after establishment in the Central North Island region (Mason in prep), and the second is a knowledge-based system which selects herbicide treatments, after site descriptions and objectives have been specified by managers (Mason *et al.* 1991). These are envisaged as major elements in a comprehensive management system, which would include decision-making, implementation, facilitation of tasks, and review of operational effectiveness, that characterise planning and controlling functions. The new tools will be briefly described, and their integration into a comprehensive management-support system for forest establishment discussed.

INITIAL GROWTH MODELS FOR RADIATA PINE

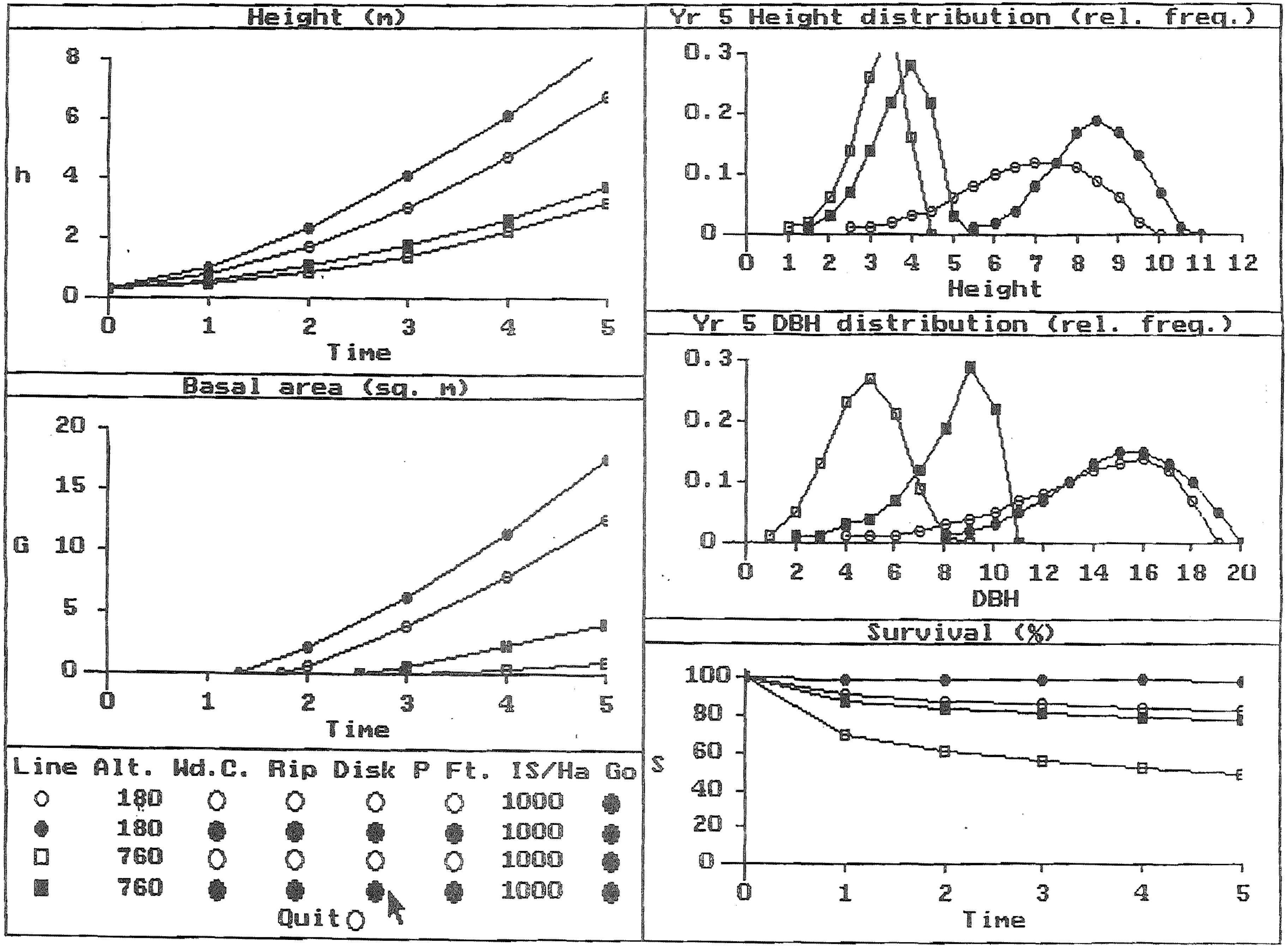
Data have been collected over the years from experiments which have monitored the early growth of radiata pine subject to different prior cultivation treatments, genetic material, initial spacing, weeding, fertilising and other such treatments on a range of sites with different inherent growth potentials. Models have been built using these data to quantify the survival and growth of young radiata pine stands. It was envisaged that managers would use the models to compare alternative establishment strategies, and to obtain starting values for models of growth and survival at older ages.

Data were obtained from 27 experiments which provided measurements of height, diameter five cm above the root collar and/or at breast height over bark (dbhob), between ages zero and six years. All trees were established through a bare-root system. Genetic quality ranged from GF 6 to GF 13, which represents low to medium rating by today's standards (Vincent and Dunstan 1989). Altitude ranged from 180 m to 1060 m above sea level. Soils were all pumice sands. Data from another 15 Nelder spacing trials indicated that there was no relationship between dbhob and initial stocking prior to age five, and that the relationship between dbhob and height of individual trees varied from site to site.

Analyses of all the data indicated that seedling survival was consistently improved by cultivation and weed control, and that growth was most improved by weed control and to a lesser extent by disc cultivation. Models incorporating these features, and the effect of altitude, provided a good indication of overall site quality. Some of the site preparation effects were interactive with altitude.

Models were developed to predict mean height, basal area, survival, maximum height, maximum dbhob, and height and dbhob variances, from which statistical parameters of Weibull probability density functions describing height and diameter distributions could be recovered. Independent variables included altitude, weed control, ripping, mounding, phosphate fertilisation, and initial stocking. Full discussion of these analyses is provided elsewhere by Mason (in prep).

A graphical user interface was built in PDC PROLOG (Prolog Development Center 1990) to provide user-friendly access to the models. A sample screen is shown in Figure I. At any given time, managers can compare four alternative survival and growth trajectories through to height and dbhob distributions at age 5. Different sites and/or treatments are specified by clicking "buttons" or entering values in the lower left hand window. To acquire more detailed views, users can click the title bar of a window to increase it to full-screen size.


Height (m)
h
Time
Basal area (sq. m)
G
Time
Yr 5 Height distribution (rel. freq.)
Height
Yr 5 DBH distribution (rel. freq.)
DBH
Survival (%)
S
Time
Line Alt. Wd.C. Rip Disk P Ft. IS/Ha Go
180 1000
180 1000
760 1000
760 1000
Quit

The effects of weed competition have not yet been well enough described within the models, as no information was available on the kinds of weed species and levels of weed infestation in the experiments. Consequently, trajectories estimating growth in the presence of weeds can be considered to be averages over a range of competition levels, and offer managers the opportunity to collect information that could lead to more discerning predictions.

This new modelling capability fills, at least partially, a gap in the New Zealand radiata pine modelling system, because earlier models could not predict growth from age 0, when tree sizes are independent of site quality, nor could they represent the effects of site preparation (Garcia 1984; Garcia 1990; West *et al.* 1982). These new models use measurements of site quality which have a biological basis (such as altitude), rather than site index (which is limited as a means of understanding processes), and represent the effects of weed control, cultivation, and fertilisation. Moreover, the new models also cater for characterising distributions of tree heights and diameters between ages 0 and 5, a capability which increases predicting and decision-making flexibility.

There is a need and an opportunity for further development of the modelling system in several respects:

1. incorporation of different competitive capabilities of different weed species;

2. inclusion of other management factors, such as effects of soil damage during harvesting, land clearing, genetics, nursery practice, propagation method, and stock handling;

3. extension of the models to other regions;

4. comprehensive user validation of models;

5. interfacing models of initial growth with those for projecting growth to older ages with due sensitivity in relation to natural site quality, management-induced changes to site quality, and tree quality (including genetics). Some of the theoretical issues relating to this aspect have been discussed by Mason (1989b), and some work relating to long-term effects of fertilisation has been conducted (Woollons *et al.* 1988).

HERBICIDE SELECTION WITH KNOWLEDGE-BASED PROGRAMMING

Knowledge-based programming techniques were employed to build a PC-based system for selecting herbicides, to improve the cost-effectiveness of vegetation management regimes and increase users' awareness of environmental hazards (Mason *et al.* 1991). Vegetation management components of forestry decision-support systems are best implemented in a knowledge-based structure. Design of vegetation management strategies or "regimes" involves many non-numerical analyses. Experienced managers acquire a qualitative understanding of the components of the problem: for example, susceptibility of weeds to different herbicides; times of year weeds are physiologically active; behaviour of weeds following alternative treatments; effects of different weeds on tree crops; and so on. This type of knowledge currently defies traditional numerical analysis.

Construction of the system proceeded in four distinct stages: an initial prototype; knowledge acquisition; coding; and a testing/adjustment cycle. A prototype system was first devised as a result of knowledge-sharing with a large private company, Tasman Forestry Ltd. Subsequently, in-depth knowledge about weed control was acquired from two sources: (i) the full extent of Tasman Forestry Ltd.'s weed control manual, and (ii) a series of interviews with Tasman Forestry Ltd. and Forest Research Institute staff. The operational system was coded in PDC PROLOG (Prolog Development Center 1990), and was refined through a series of evaluations and coding adjustments.

The program was constructed as what is called a "domain-specific shell" (Menzies 1989; Mason 1989a; Knaus & Blecker 1990). Algorithms required for herbicide selection are in compiled code, as are structures for representing different sorts of herbicides, weeds, surfactants, application methods, and their interactions. The information which makes the system specific to any given region, however, can be added to, altered or removed without further coding in Prolog. There are two programs; one for inputting knowledge (Vegetation Management Adviser), and the other for retrieval and analysis (Vegetation Management Tools). Knowledge which can be updated is stored in structures which are known as frames (Minsky 1975; Jay & Knaus 1989). These are structures which contain attributes and describe behaviours associated with particular types of objects or relations.

The expert module (Vegetation Management Adviser) is used to specify, for a given locality, the attributes of weeds, herbicides, surfactants, application methods, and their interactions. Each of these frame instances is entered on a screen with fields. Some fields have menus associated with them, some are altered simply by pressing "enter", while others ask for specific input. After frame instances have been entered, text information can be entered in an editor. When relevant to decisions, this text is accessible from the user module.

Within the user module (Vegetation Management Tools), a manager can define a site and his or her management objectives. The system can then select the most cost-effective herbicidal treatment, with or without a tree crop present, and predict the outcome of the treatment. To define a site, the user selects the weeds present from a menu, and is then taken to a screen with a set of fields. A sample screen is shown in Figure II. Many of the field values are nominated by the system from knowledge contained in frames, but this information can be overridden if the user so chooses. During the herbicide selection process, the system asks for further relevant information. It then nominates a selected herbicide, with required rates, surfactants, costs of chemicals, cost of application, and expected effects on target species (Figure III). Users are warned of any environmental hazards associated with specific chemicals, and selected herbicides can be rejected, and sub-optimal options explored.

```
                              CURRENT SITE STATE
Mean comp. index: 204     Crop Height: 0   m  % Bare: 0        Season: Spring
Mean weed height: 0.96    Crop % cover: 0     Crop S/ha:          Soil:
                                                  Cover %
          Weed                       State       top rts sds  actn Weight Ht(m)

Bracken                         Flushed/Dormant 10  10  23   Kill 27.333 1
Broom                           Mature flushed  20  20  84   Kill 23     1.2
Gorse                           Mature flushed  20  20  100  Kill 38     3
Low fertility pasture grass     Mature flushed  60  60  68   Save 5      0.2

F1=Help  F2=Trtmnt.  F3=Unreject  F4=Add weed  F5=Del. weed  ESC=Exit  F10=Sav
```

Figure II Example of site definition on input screen

Construction of this system highlighted gaps in our technical knowledge of vegetation management. For effective regimes for vegetation management to be designed, accurate models of site behaviour under different types of treatments should be developed. Two of the most important areas for research are weed biology and crop response to removal of weeds. Provision has been made within the program for recording of weed characteristics such as relative competitive ability, reproductive ability, and weed growth rate. Studies in the Central North Island have been designed to measure some of these attributes (B. Richardson *pers. comm.*).

```
                       SELECTED HERBICIDE
Herbicide:   Escort (Metsulfuron)                  Chem. cost: $35.25
Dose/ha: 500     Grams      , Water: 149.6   , Pulse      : 0.4     Litres
Operation: Spot spray               Op. Cost: $40       Total Cost: $75.25
                Anti-germination action time: 16 weeks

Spotgun            mix/20       1 container: 0.053    Litres    of Pulse
      66.667  Grams          of Escort (Metsulfuron)
```

Weed	State	% before top	rts	sds	% after top	rts	sds	DTime
Bracken	Mature dormant	10	10	23	5	5	23	8 wks
Broom		20	20	84	0	0	84	8
Gorse		20	20	100	0	0	100	8
Low fertility pasture grass	Mature flushed	60	60	68	60	60	68	0

ESC=Quit   F1=Help   F2=Accept trt.   F3=Reject   F9=Accept & print   F10=Toxicity

Figure III Expert System suggested solution on output screen

The responses of older crops to competition also need to be quantified, so that the harvestable benefits of vegetation management can be included in decision-making. Furthermore, the system should include physical control methods, and select an optimal sequence of vegetation management treatments over several years.

Two ways have been identified to achieve this aim. In both, an attempt would be made to minimise competition over time per unit cost of treatment. With existing information, a rule-based module could simulate the treatment selection activities of a current human expert. The second alternative would be more robust, and would include an accurate site model based on an enhanced version of the initial growth model described above. The module would extend the existing frame-based structure of the program, and would employ model-based reasoning (Koton 1985; Fulton & Pepe 1990).

THE TOOLS IN A MANAGEMENT CONTEXT

Decision making

These tools have demonstrated opportunities for the use of modern hardware and programming techniques to provide concise, relevant, and intelligent summaries of information relating to particular decisions required of forest managers. With the extensions suggested above, and with links to stand data bases and geographic information systems, they could form a powerful decision-support system for all aspects of plantation establishment, that can assist managers in their day to day and longer term planning in an integrated way. However, decision- makers also need to monitor progress and make appropriate changes if plans do not materialise as expected in practice.

Implementation

One of the difficulties in transferring knowledge into routine practice is a lack of familiarity with, and over-complexity of, new technology. Both the tools described here are designed specifically for operational managers to use with little or no outside help.

The vegetation management decision-support system allows users to output a hard copy prescription for a particular site, which can be relayed directly to those who are going to implement things. In a more computerised world, this might be delivered to a work crew via electronic mail, and inserted into an optimised schedule of required operations for that crew (the crew to which the message was sent having been selected by computer, based on knowledge of the people and machinery available, and their existing commitments). That, however, represents a potential for the future at present.

Facilitation

There is clearly enormous potential for knowledge-based systems in the facilitation of tasks. Expert systems, for instance, could be employed to provide training and instruction to inexperienced workers, and to solve problems as they arise. Examples relating to vegetation management would be specific, on- line assistance with chemical mixing, calibration of equipment, and tailoring of aerial herbicide application to site conditions as suggested by Richardson (1991).

Monitoring and controlling

A further potential benefit of the use of computers for helping to make operational decisions is the recording of factors leading to a decision to perform an operation on any particular site, and the comparison of projections with final outcomes. These might be projections based on mathematical models, such as the initial growth model, or projections based on qualitative models, such as a knowledge-based selection of vegetation management regimes.

Tasman Forestry Ltd., for whom the vegetation management system was originally devised, already has a management system in place to monitor the effectiveness of herbicide applications, based on hardcopy recordings of weed health at intervals after treatments have been applied. An extension to the computer-based system is planned which will record all treatments in, and transfer assessment information on outcomes to, a relational database. This will greatly facilitate the analysis of treatment cost- effectiveness.

Links are also planned to the company's stand record and geographic information systems, in order to further the use of information gathered. For example, the geographical distribution of particular weed species could be identified after a sufficient number of vegetation management decisions had been made through the support system, as all site descriptions would be linked to geographical locations.

OBSERVATIONS ON PROGRAM STRUCTURES

Development of these two tools has led to the following recommendations about the types of structures which decision- support system developers should adopt.

Firstly, managers are constantly confronted with change, not just in regulations, materials and methods, but in information technologies. The systems envisaged here represent a considerable investment in scientific study, knowledge representation, and computer programming. It is highly desirable, therefore, to create systems which can evolve without becoming wholly obsolete.

Secondly, the systems should represent the real world in ways which are amenable to processing of data and concepts. The vegetation management system would have been much harder to develop without the use of frames.

Thirdly, to be useful, programs must be user-friendly, with on-line help and clear presentations. Graphical presentation of the initial growth model, for example, enables managers to visualise much better the results of their actions.

Fourthly, tools must be capable of being integrated in a seamless fashion. Managers are unlikely to want to spend time massaging output from one program to conform to input standards for another.

Object oriented programming, such as that using languages like Smalltalk (Digitalk 1991) or C++ (Borland 1990), provides many of the required features. Program structures in these languages consist of a hierarchical arrangement of objects, which can represent real-world relations. Each object contains relevant data and behaviours; that is, it knows how to behave when sent an instruction. For instance, to obtain growth projections from a set of stands, a program would send the stand objects a message to grow themselves. The message sender would not have to know how this was accomplished in each stand. Frames can be easily and naturally represented in such a paradigm. In addition, object oriented programming has proved to be a potent way to code user-friendly interfaces between humans and computers, because many of the features of a graphical user interface are best configured as independent objects.

An important feature of an object-oriented language is the ease of updating and facility to integrate tools developed by different programmers. Objects provide a natural modularity, and programs can be improved incrementally, provided that the original object hierarchies selected properly represent the system being modelled.

CONCLUSIONS

Intensive plantation management demands sensitive planning and control systems. Managers need to rely on refined technology that assists them in making good decisions and monitoring their success.

Two new computer-based tools designed to assist managers around time of plantation establishment indicate the potential for researchers to provide comprehensive, user-friendly computer systems which can produce up-to-date, concise, carefully-crafted recommendations to managers at all levels. This should result in more efficient and independent use of both information and of managers.

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